U.S. Coast Guard Research and Development Center
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Historical Summary of Aids to Navigation Analyses

Volume I

FINAL REPORT
APRIL 1998

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NOTICE

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16. Abstract

Volume I (this volume) contains an integrated description of over 225 studies, analyses, and papers that were identified as part of the historical summary of aids to navigation analyses. The studies include 137 studies that have been reviewed in detail and for which an annotated bibliography has been prepared (Volume II). Another 31 relevant studies have been identified that are part of the analysis in Volume I. A total of 59 studies conducted by the Coast Guard Research and Development Center that focus on buoy technology, moorings, and hardware are summarized and categorized. The report includes reviews of the studies and their interrelationships based on their functional similarities. In particular, studies are grouped by aid technology, aid use and waterway design, service force mix, aid positioning, advanced technologies, and cost. The various models and analyses have been evaluated to determine what methods and models will continue to be useful to the Program Manager. A number of unresolved issues have also been identified that provide direction for future analysis. In total, this document contains an impressive summary of many years of detailed analysis that has been undertaken by the Short Range Aids to Navigation program and the Radionavigation Aids program to improve the level of service to the mariner and to reduce the cost to the taxpayer of providing that level of service.

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Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
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mi^2	square miles	2.6	square kilometers	km^2
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tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
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yd^3	cubic yards	0.76	cubic meters	m^3
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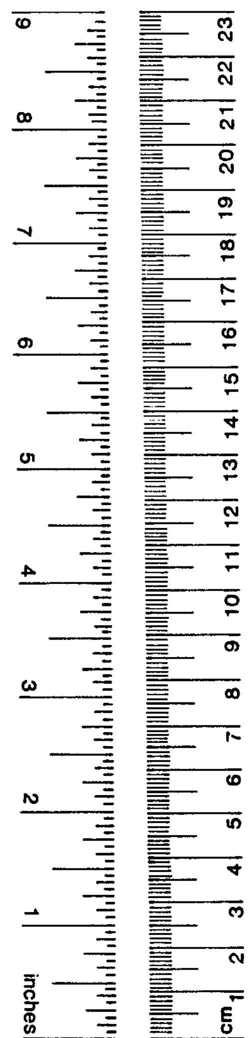
*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

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m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
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kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
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m^3	cubic meters	1.3	cubic yards	yd^3
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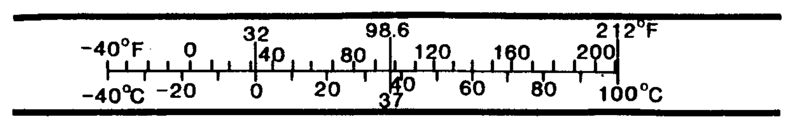
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

The Coast Guard is continually attempting to identify ways to improve the level of services offered to mariners and reduce the costs of doing so. The Short Range Aids to Navigation (SRA) program and the Radionavigation Aids (RA) program have made major efforts to achieve that continuous improvement. There have been numerous studies over the years that have addressed buoy technology, hardware and moorings. The resulting improvements have revolutionized the servicing requirements and subsequently changed the frequency of servicing from once every three months to once every two years. Those changes have led to reduced levels of servicing resources and associated costs. Even so, aids to navigation programs represent nearly 25% of the Coast Guard's operating budget. At the same time, more accurate and reliable electronic navigation capabilities are being developed and there is the possibility of moving from "*iron to silicon*" as a primary means of navigation.

The purpose of this study is to examine the rich history of studies and analyses that have been completed over the years in support of the aids to navigation program. The objective of this examination is to identify whether there are important insights that have been observed in the past but overlooked and never implemented, and whether any of the analytical approaches that have been used in the past remain valid tools for future analyses. Specific tasks in the current study include reviewing past analyses, conducting a technology survey, and examining cost analyses. Although the statement of work limited the review to studies conducted by the Coast Guard, there are a number of studies conducted by other agencies that are relevant and are included. A total of 227 studies involving various aspects of the SRA program and portions of the RA program in the Harbor and Harbor Entrance domain have been identified. Of those, 137 studies have been reviewed in detail, 59 studies conducted by the Coast Guard Research and Development Center that have focused on buoy technology, hardware and moorings have been identified, and another 31 relevant studies have been identified through secondary references. The result represents a very substantial history of research and analysis supporting the aids to navigation programs. Six areas are used for summarizing the studies and analyses in this volume.

Studies Focusing on Aid Technology, Buoy Hardware, Moorings, Maintenance, Logistics, and System Support:

- *Buoy/Beacon Design, Hardware and Moorings*--this includes a number of major studies as well as some technical studies conducted by the Research and Development Center.
- *Buoy Tender Technology*--this includes studies that examined alternative hulls as well as operating characteristics that affect the development of replacement vessels.
- *Maintenance and Logistics*--this primarily involves support facilities and maintenance policy issues.
- *Personnel Requirements*--this includes issues involving the assignment and training of personnel qualified for aids to navigation work.

Studies Focusing on Aid System Use and Waterway Design:

- *Aid System Performance Measures*--this category includes studies that focused on how well an aid system worked and attempts to measure that outcome.

- *Customer Identification/Requirements*--this includes studies that addressed particular customer needs and information required for safe navigation.
- *Navigability, Safety, Risk*--this includes various analyses that addressed safety and risk from a navigability perspective (generally not explicitly involving the use of aids) that would affect the design of the waterway. Broad systems risk analyses are included here.
- *Waterway Design (Aid Location, etc.)*--this is another broad category that includes those studies and analyses that attempt to shed light on what factors are important in designing a waterway, particularly with respect to what aid related factors are important.

Studies Focusing on Positioning:
- *Aid Positioning*--this involves both manual and electronic means of positioning aids.
- *Vessel Positioning*--this includes studies that focused on enhancing the ability of a vessel to determine its position more accurately and reliably.

Studies Focusing on Servicing Force Mix:
- *ATON Policies*--this broad category generally includes issues such as discrepancy response and servicing interval policies.
- *Information Requirements/Systems*--this includes broad information needs for the operation of the programs.
- *Servicing Mix*--this includes a myriad of studies and analyses that address the combinations of servicing resources needed to deploy and maintain the aids to navigation systems.

Studies Focusing on Advanced Technologies:
- *Advanced Technology (DGPS, ECDIS, ARPA, etc.)*--this includes most of the electronic means of navigation including bridge electronics.
- *Radionavigation Aids*--this includes those electronic systems that were intended to provide general navigation information as well as the use of those systems.

Studies Focusing on Cost Issues:
- *Operating Costs*--this includes an explicit consideration of the cost of only the component being examined.
- *Systems Cost Issues*--this includes a consideration of a systems cost, and may incorporate the subsystem or component/alternative cost.

Many of the models and results provide a sound basis for further examination of the aid mix problem The most recent model to address the service force mix is the Service Force Mix (SFM) DSS developed by the Volpe National Transportation Systems Center in 1972 and used in the SFM 2000 study and follow on analyses of WLIC and BUSL requirements. The SFM DSS is a reasonable model to evaluate the adequacy of an assigned set of servicing forces. It uses composite time estimates when creating the various tours that select the aids to be serviced on a particular trip. The sensitivity results from the model are very useful for evaluating the effects of service time changes, such as improvements in the time to position an aid using the new dynamic positioning system with DGPS. The model is robust in its ability to be applied to all classes of buoy tenders and buoy boats.

The results of a number of years of man-in-the loop simulation studies has facilitated the development of the *Waterways Design Manual* that provides supplementary guidance for aid selection and arrangements for marking waterways. The manual includes a model for estimating the Relative Risk Factor (RRF) that can be used to compare alternative waterway and aid designs for a specified design vessel. The RRF remains a viable tool for its intended purpose. It is not an absolute measure and it does not provide the capability to compare across waterways. The Waterways Evaluation Tool (WET) under development is designed to be used across waterways, but structural limitations will limit that ability.

Simulation methods were used to evaluate various servicing alternatives. Other simulation methods of interest are those used to represent or evaluate the performance of aid systems and navigation aids. No operating fast time simulation model that obtains position information from visual aids has been identified. The dominant use of simulation has been the use of man-in-the-loop simulators, principally at MSI/CAORF and at the USCG Academy (SCANTS), to evaluate the system performance in the presence of various visual and radionavigation aids, including DGPS and ECDIS. This simulation method has proven very effective in evaluating aid arrangements and the use of various electronic displays. It remains a viable tool for future evaluation.

The study identified a number of unresolved issues. Aid development issues include the role of articulated beacons, progress in plastics for buoy bodys, extended life lighting systems, and how to increase guano resistance of solar panels and buoy paint. Service Force Mix issues include a five year validation of the 1994 Short Range Aids to Navigation Mission Analysis (SRAMA), identification of required surge capacity, evaluating the effect of the recent servicing policy changes, and evaluating the system effects of reducing the number of aids. With respect to aid mix, issues include examining the trade-off between visual aids and DGPS/ECDIS, identifying cognitive models for obtaining meaningful position information from visual aids or from electronic displays, and evaluating the sensitivity of user differences with respect to aid mix. Cost issues include identifying controllable costs that would be affected by program change decisions. Analysis issues include developing and maintaining an analysis capability by Program Manager, and identification of analytical models that must be maintained by Program Manager. Advanced technology issued include determining how small users benefit from technology advances (e.g., DGPS) if they do not have ECDIS or ECS capability, and identifying the scope of applicable areas for advanced technologies?

A second report (Volume II) includes an annotated bibliography of the 137 studies that were reviewed in detail.

1.0 INTRODUCTION

The Coast Guard is continually attempting to identify ways to improve the level of services offered to mariners and reduce the costs of doing so. The Short Range Aids to Navigation (SRA) program and the Radionavigation Aids (RA) program have made major efforts to achieve that continuous improvement. There have been numerous studies over the years that have addressed buoy technology, hardware and moorings. The resulting improvements have revolutionized the servicing requirements and subsequently changed the frequency of servicing from once every three months to once every two years. Those changes have led to reduced levels of servicing resources and associated costs. Even so, aids to navigation programs represent nearly 25% of the Coast Guard's operating budget. At the same time, more accurate and reliable electronic navigation capabilities are being developed and there is the possibility of moving from "*iron to silicon*" as a primary means of navigation.

As the challenge to increase services and reduce costs continues, it is valuable to review past efforts and identify whether there are important insights that have been observed in the past but overlooked and never implemented, and whether any of the analytical approaches that have been used in the past remain valid tools for future analyses. The Aids to Navigation Program Manager has tasked the Coast Guard Research and Development Center to coordinate such a review. This study, the purpose of which is to look at the rich history of studies and analyses that have been completed over the years in support of the aids to navigation programs, responds to that tasking.

Specific tasks in the current study include reviewing past analyses, conducting a technology survey, and examining cost analyses. Specifically, the statement of work required a review of all previous SRA/RA studies conducted by the Coast Guard from 1970 to the present. The technology survey task required an identification of the technologies in use at the time of the various studies and an assessment of what technologies are candidates for implementation in the future. A separate analysis of costing of program activities was envisioned in the task structure, but initial attempts by the Research and Development Center to develop such a cost structure was met with some resistance at headquarters administrative levels. Therefore, the cost segment of this historical summary includes an assessment of how costs were developed in various studies and to what extent cost was an explicit consideration.

Although the statement of work limited the review to studies conducted by the Coast Guard, there are a number of studies conducted by other agencies that are relevant and have been included. A total of 227 studies involving various aspects of the SRA program and portions of the RA program in the Harbor and Harbor Entrance domain have been identified. Of those, 137 studies have been reviewed in detail, 59 studies conducted by the Coast Guard Research and Development Center that have focused on buoy technology, hardware and moorings have been identified, and another 31 relevant studies have been identified through secondary references. The result represents a very substantial history of research and analysis supporting the aids to navigation programs.

The primary purpose of this volume of the final report is to provide a detailed description of the relationships among the studies, evaluate the methodologies used,

determine what recommendations were and were not implemented, identify any viable alternatives that were not implemented, and assess the usability of the methodologies for the future. A second report (Volume II) includes and annotated bibliography of the 137 studies that were reviewed in detail. References in this report that are included in Volume II are identified with an index number in brackets in the reference listing. Volume I (this report) is organized as follows. A brief description of the Coast Guard Aids to Navigation program is provided, followed by an overview of the aids to navigation studies, analyses, and papers to give a chronological perspective and create a context for understanding the various results. These sections are followed by separate sections that focus on particular classifications of analysis by functional area (e.g., aid system use and waterway design, servicing force mix, positioning, advanced technology). The report concludes with an overall assessment of the future usability of the results and an identification of unresolved issues.

2.0 OVERVIEW OF COAST GUARD AIDS TO NAVIGATION

Title 14 of the United States Code authorizes and requires the Coast Guard to establish and maintain aids to navigation. This responsibility was inherited from the Lighthouse Board in 1939 and has represented approximately one-fourth of the Coast Guard's operating budget since then. The Coast Guard is responsible both for short range aids to navigation as well as radionavigation aids, the majority of which cover open ocean areas. The primary focus in this overview is on SRA. A complete overview of the SRA mission is included in Brown, Blythe, Schwenk, and West (1993). A summary description is included in the SRAMA study (US Coast Guard, 1994b). Both sources were used for this overview. The description below characterizes the program in 1993 and represents the Coast Guard as it was when most of the major resource studies were conducted. Since then, the number of aids to navigation have increased by about 500 and two new JUNIPER class buoy tenders and two new KEEPER class buoy tenders have entered the fleet.

Short range aids include lights (major and minor), daybeacons, lighted and unlighted buoys, and various electronic and audible signals. When the Coast Guard absorbed the Lighthouse Board and its responsibilities in 1939, there were about 33,000 Federal aids for which the Coast Guard became responsible. The total Federal aids increased at an average 0.94% annual rate to reach 44,100 aids in 1970 and then at an average annual rate of 0.61% to reach the 1993 total of 50,698 Federal aids. Not included in this total are approximately 48,000 private aids to navigation for which the Coast Guard has permitting and inspection responsibility. The changes in the numbers of aids by type between 1970 and 1993 are illustrated in Table 2.1.

Table 2.1: Aid Population Changes, 1970-1993.

Aid Type	Number of aids (1970)*	% of aids (1970)	Number of aids (1993)**	% of aids (1993)
Buoys				
Lighted	4,200	9.5%	4,431	8.7%
Unlighted	21,900	49.7%	20,402	40.3%
TOTAL BUOYS	26,100	59.2%	24,833	49.0%
Lights			12,084	23.9%
Daybeacons			10,970	21.6%
TOTAL STRUCTURES	18,000	40.8%	23,054	45.5%
Other	0	0%	2,811	5.5%
TOTAL AIDS	44,100	100%	50,698	100%

* Booz-Allen (1970a) ** Brown et al. (1993)

Aid technology has changed dramatically over the past thirty years. Acetylene and lead-acid batteries were used to power buoy lights until the mid-1960s when they were phased out in favor of non-rechargeable carbon zinc batteries. In the 1970s, radar reflectors, transistorized flashers, and photo cell daylight controls were added as standard equipment. Solar powered aids with rechargeable batteries were introduced in the mid-1980s. Dayboard materials have been developed that now have a life expectancy approaching six years. These developments have affected the servicing requirements.

Four types of routine servicing actions are performed on Federal aids to navigation:

- *Inspection*--aid is cleaned and painted, its position and voltage checked; material and lamps are replaced as needed, and solar panels cleaned, at least annually.
- *Recharge*--batteries of a lighted aid (lighted buoys and lights) are replaced every three years for aids powered by standard batteries and every five years for solarized aids.
- *Mooring Inspection*--underwater mooring of lighted and unlighted buoys is examined every two years and, if necessary, cleaned, repaired, and/or replaced.
- *Relief*--body of a lighted or unlighted buoy is replaced every six years.

Seasonal buoys typically require two annual visits, one for removal and one for replacement. Riverine buoys in open rivers are moved and placed periodically as water levels change. In addition to routine servicing, major lights require periodic structural maintenance, and all aids require discrepancy response servicing when the primary signal fails, the aid is destroyed or missing (e.g., vessel allision with a light or daybeacon, mooring breaks and buoy carried away by the current), or a buoy is reported to be off-station.

Aids may be serviced by vessels, small boats, or by motor vehicle depending on the location and type of aid. Vessels include the following types:

- *WLB*--large, stable, heavy-lift seagoing buoy tender capable of servicing the largest buoys located offshore.
- *WLM*--lighter coastal buoy tender servicing medium-sized buoys in coastal waters.
- *WTGB/Barge*--icebreaking tug pushing a crane-equipped barge servicing heavy buoys in semi-exposed locations.
- *WLI*--inland buoy tender operating in rivers and less exposed inland waterways servicing small to medium-sized buoys.
- *WLIC*--inland construction tender that builds or rebuilds fixed aids to navigation (daybeacons and minor lights).
- *WLR*--river buoy tender typically consisting of a pusher towboat with an attached crane-equipped barge.

Shore-based Aids to Navigation Teams (ANTs) use a variety of small boats including 55' Aids to Navigation Boats (ANB) and 46'-49' stern loading buoy boats (BUSL). Changes in the number of vessels used to service aids to navigation from 1970 to 1993 are illustrated in Table 2.2.

In FY 1993, operating expenses for the short range aids to navigation program were $382 million. If LORAN-C is included, the operating expenses total $497.3 million. Approximately 4,000 Coast Guard employees are involved in the aids to navigation program. The program manager, staff, and support personnel at Coast Guard headquarters are responsible for overall planning, policy development, and resource acquisition. The direct operation of the program is conducted at the nine Coast Guard district offices that direct the activities of the operational units, primarily cutters and ANTs, in accomplishing the program mission. A significant amount of local planning, within the parameters provided by the Commandant, is conducted at the district level,

including all resource management. A number of headquarters units provide important support activities (e.g., Maintenance and Logistics Command, Coast Guard Research and Development Center) as well. The servicing resources in 1993 are summarized by district in Table 2.3.

Table 2.2: Change in Servicing Resources for Aids to Navigation, 1970-1993.

Vessel Type	Number in 1970*	Number in 1993**
WLB/WLM	53	37
WLI/WLIC	32	22
WLR	25	18
WTGB/Barge	0	2
ANT	0	64

* Booz-Allen (1970a) ** Brown et al. (1993)

Table 2.3: ATON Servicing Resources by District*.

District	Geographic Area	WLB	WLM	WLI	WLIC	WTGB/ Barge	WLR	ANT	ATON
1	NE US	3	5	0	0	0	0	9	5,686
5	Mid-Atlantic	3	3	2	3	0	0	9	6,747
7	SE US	2	1	0	5	0	0	9	6,401
8	Gulf Coast	2	2	0	8	0	0	17	8,409
8**	Rivers	0	0	0	0	0	18	0	15,237
9	Great Lakes	3	0	1	0	2	0	9	2,582
11	California	2	0	0	0	0	0	4	2,022
13	Pacific NW	2	0	2	0	0	0	5	1,889
14	Hawaii	3	0	0	0	0	0	1	506
17	Alaska	6	0	1	0	0	0	1	1,219
Total		26	11	6	16	2	18	64	50,698

* Brown et al. (1993) ** formerly the 2nd CG District

More details describing the aids and their specific characteristics and use, and the capabilities and use of the servicing forces are included in the 1983 Short Range Aids to Navigation Study (US Coast Guard, 1983), the Service Force Mix 2000 Study (Brown et al. 1993; Brown and Schwenk, 1992), the Construction Tender Study (Brown, Bucciarelli, and Leo, 1994), the Buoy Boat Study (Brown, 1993), and the Short Range Aids to Navigation Mission Analysis (US Coast Guard, 1994b).

3.0 OVERVIEW OF AIDS TO NAVIGATION ANALYSES

3.1 Background

The responsibility for establishing and maintaining aids to navigation was transferred to the Coast Guard in 1939 from the Lighthouse Board along with the resources necessary to accomplish the mission. The various functions performed by the Lighthouse Board were fractionated within the Coast Guard with primary responsibility for operational aspects assigned to the Aids to Navigation Division. Following World War II, the Coast Guard experienced a severe reduction in personnel and appropriations without a proportionate reduction in services provided, and the phrase "taking out of the hide" came into common usage (Armacost, 1977). In 1948, a study by Ebasco Services, Inc. concluded that many of the missions of the Coast Guard were ill-defined, some were not authorized by Congress, and no long range planning was being conducted. The Coast Guard's responsibilities were clearly delineated in a 1949 revision to Title 14, and in 1953, the Aids to Navigation Manual (CG-222) was published for the first time, but it did not include sections on administration and planning. Following the Korean War, there was a need for substantial replacement of Coast Guard facilities, but no effective planning for facility replacement was being conducted. Between 1959 and 1962, the Coast Guard developed three basic facility plans (cutter, aircraft, and shore units) that focused on facility acquisition and budget justification. In 1962, the Secretary of the Treasury approved the first study of the ten "Roles and Missions" of the Coast Guard. The Roles and Missions Study and the facilities plan provided a basis for program and facility planning. With respect to aids to navigation, the Roles and Mission Study concluded that

> "The present aids to navigation system is meeting the needs of commerce and national defense, expanding moderately in the process. In providing the changes and improvements required by maritime activity, river and harbor work, and natural causes, the Coast Guard uses definite criteria which assure economical and efficient operation." (US Treasury Department, 1962, p. D-92)

Following the 1962 Roles and Missions Study, several studies, largely in the form of officers' Master's theses, provided necessary input to decisions resulting in increasing the staffs of District offices and reorienting the focus for planning to a mission-orientation. These studies paralleled the efforts taking place in the Coast Guard at large at that time.

3.2 Aids to Navigation Planning Perspective

In 1966, the General Accounting Office conducted an evaluation of buoy tender utilization in the First Coast Guard District. The results of this study immediately led to the reassignment of a WLB to oceanographic duties, and more importantly, led to a Coast Guard wide buoy tender utilization study. In 1967, the Coast Guard was transferred to the newly formed Department of Transportation. The transfer was accompanied by an "administrative General Quarters" that resulted in numerous issue studies. The issue paper that focused on buoy tender utilization led to several significant resource change recommendations and recommended a comprehensive analysis of the entire aids to navigation system (US Coast Guard, 1967). At the same

time, several persons in the Aids to Navigation Division were working with the Federal Aviation Administration to develop a "National Plan for Navigation" that would address radionavigation needs.

Following these initial efforts, official commitments were made to develop a National Navigation Plan and to conduct an Aids to Navigation Study. With insufficient personnel to conduct both simultaneously, a single National Navigation Planning (NNP) staff was formed to coordinate both efforts. The NNP staff completed the National Plan for Navigation in 1970. Additionally, it managed several large contracts and conducted various analyses within the staff that formed the basis for planning in the aids to navigation program.

3.3 Scope of Aids to Navigation Analyses Considered

In the 30 years since the Aids to Navigation issue paper following the administrative General Quarters, there has been a large number of studies and analyses that have addressed various aspects of the aids to navigation program. In particular, these studies have focused on

- hardware development and related issues,
- the mix of servicing forces that are required to operate the systems of aids,
- developing an understanding of how aids are used by the mariner and how to design better waterways, and
- measuring the performance of systems of aids to navigation and the performance of waterways.

More than 160 references are listed in this report that represent the significant analyses that have affected the content of the program and the resources used to accomplish the program mission. The primary sources for this summary include research reports from Coast Guard sponsored contracts, internal Coast Guard studies conducted by the program manager and various support managers, studies conducted at the district level, and studies sponsored by other agencies that are related to the aids to navigation mission. A total of 137 of the studies and analyses are reviewed and described in an annotated bibliography in Volume II of this report.

There are many possible means of classifying the various studies. In Volume II of this report, each study was identified with one Primary classification and as many Secondary classifications as seemed appropriate using nineteen different categories. In summarizing the studies and analyses in this volume, those categories have been grouped into six areas as follows.

Studies Focusing on Aid Technology, Buoy Hardware, Moorings, Maintenance, Logistics, and System Support:

- *Buoy/Beacon Design, Hardware and Moorings*--this includes a number of major studies as well as some technical studies conducted by the Research and Development Center.
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- *Personnel Requirements*--this includes issues involving the assignment and training of personnel qualified for aids to navigation work.

Studies Focusing on Aid System Use and Waterway Design:
- *Aid System Performance Measures*--this category includes studies that focused on how well an aid system worked and attempts to measure that outcome.
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- *Navigability, Safety, Risk*--this includes various analyses that addressed safety and risk from a navigability perspective (generally not explicitly involving the use of aids) that would affect the design of the waterway. Broad systems risk analyses are included here.
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- *Aid Positioning*--this involves both manual and electronic means of positioning aids.
- *Vessel Positioning*--this includes studies that focused on enhancing the ability of a vessel to determine its position more accurately and reliably.

Studies Focusing on Servicing Force Mix:
- *ATON Policies*--this broad category generally includes issues such as discrepancy response and servicing interval policies.
- *Information Requirements/Systems*--this includes broad information needs for the operation of the programs.
- *Servicing Mix*--this includes a myriad of studies and analyses that address the combinations of servicing resources needed to deploy and maintain the aids to navigation systems.

Studies Focusing on Advanced Technologies:
- *Advanced Technology (DGPS, ECDIS, ARPA, etc.)*--this includes most of the electronic means of navigation including bridge electronics.
- *Radionavigation Aids*--this includes those electronic systems that were intended to provide general navigation information as well as the use of those systems.

Studies Focusing on Cost Issues:
- *Operating Costs*--this includes an explicit consideration of the cost of only the component being examined.
- *Systems Cost Issues*--this includes a consideration of a systems cost, and may incorporate the subsystem or component/alternative cost.

The following two areas involved approaches rather than objectives and they serve as secondary classifications only.

- *Human Factors*--this includes studies that have a significant involvement with the role of the human in aids to navigation, including information processing and use of navigation aiding devices.
- *Modeling and Analysis*--this includes studies that have used a significant amount of model development and analytical approaches to represent and evaluate aid system elements.

The influences among the major elements in aids to navigation systems are illustrated in Figure 3.1.

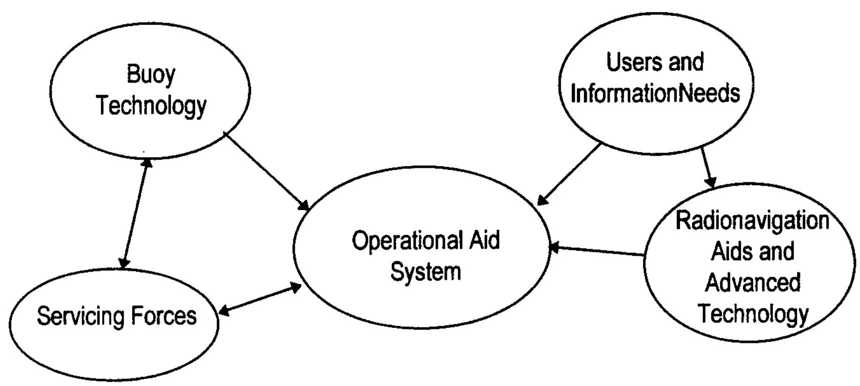

Figure 3.1. Aids to Navigation System Elements Influence Diagram.

In addition, 59 studies that were conducted by the Coast Guard Research and Development Center and that focus on aid technology/design, hardware, and moorings were identified as well. However, these studies were not reviewed because they were perceived to have value as historical documents, but would have little effect on future aid system designs. Current issues are included in the reviewed studies.

In the following sections, the significant results and relationships among the studies in each of the six groups are discussed. Where possible, the significant recommendations of each study and their implementation are evaluated.

4.0 SUMMARY OF STUDIES FOCUSING ON AID TECHNOLOGY, BUOY HARDWARE, MOORINGS, MAINTENANCE, LOGISTICS, AND SYSTEM SUPPORT

4.1 Buoy Technology Advances

The quality, accuracy, and reliability of the signal provided to the mariner depends on the technology used in the aid and the way that technology is implemented in the field. The technology includes both a signal (e.g., shape, color, light, sound, electronic) and a device for displaying the signal (e.g., buoy, structure). Basic technologies for fixed and floating aids were well established by the time the Coast Guard assumed responsibility for 33,000 Federal aids in 1939. Coast Guard engineers continued to explore new technologies for aids to navigation. By the late 1960s, acetylene buoys had been replaced by lighted aids using batteries and multi-place lampchangers. Today, most aids are operated using solar power with rechargeable batteries. There have been changes in the shape and materials used for buoys and structures. An overview of the aids that are available today is included in Brown (1993) and a more detailed description of the aids and their characteristics is included in the Short Range Aids to Navigation Mission Analysis, SRAMA (US Coast Guard, 1994b).

The Coast Guard Research and Development Center reports provide a strong background on aid development. The 59 studies that were not reviewed in detail have been classified using the following criteria.

- *Aid Use*--this includes optical and other considerations for use of visual aids.
- *Mooring*--this includes various systems that affect the moorings of buoys.
- *Power*--this includes various studies that examined alternative power sources for aids.
- *Design*--this includes studies that examined alternative shapes and materials for aids.
- *Other*--this includes studies regarding positioning and buoy tenders.

4.1.1 Aid Use Studies

Table 4.1 includes those R&DC studies that involved various aspects of aid characteristics that affect how the aid is used and its effectiveness in providing an appropriate signal. The focus is on ranges, laser lights, and visibility aspects of lights. Several of the reviewed studies in the annotated bibliography address some of these aspects of aid use. Thacker (1984) examined the effects of flashtube characteristics and developed a model to predict user performance based on flashtube operating parameters (repetition rate, flick frequency, and number of flicks in a multiflick flash). Winslow and Mandler (1986) compared laser light with a traditional light source and found that at "practical" design illuminance levels, no significant conspicuity advantage would be gained by replacing existing navigational aids with laser aids to navigation. Wroblewski and Mandler (1990) studied the effect of buoy motion on detection range and found that the actual range at which an observer has an 80% probability of detecting the light is about half of the nominal range that is published. Increasing the lantern divergence would increase the actual detection range about 40%. Laxar, Luria, and Mandler (1990) found that under certain conditions, single-station ranges could provide navigational sensitivity comparable to parallax ranges, but involved greater uncertainty on the part of the observer.

Table 4.1: R&DC Studies on Aid Use.

R&DC No.	Date	Title
9/74	Apr 74	Design, Construction and Evaluation of a Laser Range Light
13/74	Apr 74	Illumination Levels Within Aids to Navigation Lanterns at Sunrise and Sunset
16/85	Jan 86	An Evaluation of the Inogon Leading Mark
6/87	Aug 87	Probabilities of Detecting and Recognizing Flashing Lights on Rolling Buoys
8/87	Mar 87	St. Louis Harbor Electroluminescent (EL) Bridge Lighting Project
14/87	Aug 87	Detection and Identification of Fluorescent and Non-Fluorescent Daymark Materials
19/87	Dec 87	Development of a Chromatic/Luminance Contrast Scale
8/89	Mar 90	Assessment of Pilot Needs for Shipboard Data and Informational Documents
1/90	Jan 90	Navigation Performance Using Parallax Range Lights
15/91	Apr 93	A Comparison of Simulated Parallax and Single-Station Range Aids to Navigation: Final Report

4.1.2 Aid Mooring Studies

Research and Development Center studies involving buoy mooring systems are summarized in Table 4.2. These studies have examined wear of buoy chain, sinker movement, and alternative mooring system structures. Debok and Walker (1979) used historical mooring failure data to identify buoy station characteristics associated with identified failure rates.

Table 4.2: R&DC Studies on Aid Moorings.

R&DC No.	Date	Title
16/75	Jun 75	Lightweight Anchors for Small Buoys--A State-of-the-Art Survey and Feasibility Study
22/75	Sep 75	Synthetic Mooring Line Tensile Testing Procedure
29/75	Oct 75	Computer Mooring Simulation of Rubber Band Mooring on a 8x26 Navigational Buoy and an 8-foot Diameter OSI Buoy
10/76	Dec 75	A Feasibility Study of Extending the Jetting Process on the Western Rivers
13/76	Jun 76	Development, Test and Evaluation of an Explosive Embedment Anchor for Use in the Mooring of Small Coast Guard Buoys
28/77	Oct 77	Characterization of the Movement of Sinker During Deployment
9/82	Jun 82	A Snapback Evaluation Technique for Synthetic Lines
12/82	Jun 82	Rotational Loading of Double-Braid Line Eye Splices
5/86	Apr 86	Corrosive-Wear of Buoy Chain
2/88	Jan 88	Corrosive-Wear of Buoy Chain

4.1.3 Aid Power System Studies

A significant amount of work has been conducted on power systems for aids. Table 4.3 includes a summary of the R&DC studies in this area. The significant advance in this area has been the extensive use of solar power with lead-acid batteries for lighted aids.

Table 4.3: R&DC Studies on Aid Power Systems.

R&DC No.	Date	Title
5/76	Jun 76	Laboratory Evaluation of Solar Power Units for Marine Navigation
18/76	Jun 77	Computer Program for Design and Performance Analysis of Navigation-Aid Power Systems Program Summary
18/76	Jul 77	Computer Program for Design and Performance Analysis of Navigation-Aid Power Systems Program Documentation, Volume I - Software Requirements Document
18/76	Jul 77	Computer Program for Design and Performance Analysis of Navigation-Aid Power Systems Program Documentation, Volume II - Users Manual
18/76	Jul 77	Computer Program for Design and Performance Analysis of Navigation-Aid Power Systems Program Documentation, Volume III - Programmers Manual
22/77	Sep 77	Coast Guard Evaluation of a Wave Activated Turbine Generator Buoy
11/78	Jun 78	Economic Analysis of Solar Photovoltaic for Low Power Lighted ATON
20/78	Dec 78	CG Marine Exposure Facilities for Naturally Aging Solar Photovoltaic Modules
7/79	Mar 79	Evaluation of Solar Photovoltaic Arrays for Use on Marine Aids to Navigation
12/80	Nov 80	Evaluation of Solar Photovoltaic Energy Storage for Aids to Navigation
13/80	Nov 80	Testing Solar Photovoltaic Arrays for Utilization on Marine ATON
25/81	Sep 81	Accelerated Stress Testing of Solar Photovoltaic Modules
29/81	Dec 81	Lead-Acid Batteries in Solar Photovoltaic Power Systems for Marine Aids to Navigation
9/86	Aug 86	The Maintenance and Operation of a Small Wind Generator in the Marine Environment
9/88	Oct 89	The Development of a Charge Algorithm for the Optimized Charging of a 120V Flooded Lead-Acid Lighthouse Battery with Forced Electrolyte Destratification
14/88	Oct 88	Evaluation of Fuel Cell Technology for Coast Guard Applications
4/89	Nov 89	Test and Development of a Microprocessor Controlled Cycle-Charging Power System for Remote Lighthouse Applications

4.1.4 Aid Design Studies

There has been significant research into questions regarding buoy and structure design. Major objectives are to increase the reliability of the aid, reduce maintenance, improve performance, and reduce servicing requirements. Table 4.4 includes R&DC studies involving aid design. Key resources in that table include the documentation of the 1990 worldwide buoy technology survey. In 1978, Grossetti, Prime, Campbell, and Moukawsher (1978) had developed an initial buoy reference library. The report contained references to books and papers as well as a list of buoy manufacturers. The reports were arranged in seven categories: (1) mooring systems, (2) power sources, (3) development and design, (4) applications and uses, (5) instrumentation, math and computer models, (6) characteristics, and (7) miscellaneous. Fixed and floating breakwaters were addressed separately.

Table 4.4: R&DC Studies on Aid Design.

R&DC No.	Date	Title
20/76	Dec 76	Lightweight Lighted Buoy Development for Use as Discrepancy Navaids
1/77	Dec 76	Lightweight Low Drag Fast Water Buoys
22/81	Nov 81	Design of an Articulated Spar Buoy
3/85	Mar 86	The Design and Model Testing of a Collision Tolerant Pile Structure
11/90	Feb 91	Worldwide Buoy Technology Survey, Vol. I
11/90	Feb 91	Worldwide Buoy Technology Survey, Vol. II
11/90	Feb 91	Worldwide Buoy Technology Survey, Vol. III
11/90	Feb 91	Worldwide Buoy Technology Survey, Vol. IV
12/90	Mar 90	Life Cycle Cost Analyses of Dayboard Systems
13/90	Mar 90	Technical Evaluation of Dayboard Materials
1/91	Nov 90	Non-Destructive Evaluation (NDF) of Fiberglass Marine Structures State-of-Art Review
9/92	Jan 93	Evaluation of 5-year Dayboard Materials
16A/92	Nov 92	Development of a Test Program to Evaluate Structural Defects in Glass Reinforced Plastic (GRP), Vol. I
16B/92	Nov 92	Development of a Test Program to Evaluate Structural Defects in Glass Reinforced Plastic (GRP), Vol. II
	Jul 95	Light Emiting Diode (LED) Red Buoy Light

Dadiola, Basar, Johnson, and Walker (1990) reviewed the research and development efforts on buoys by the Coast Guard since 1962. The results were based on an extensive literature survey and interviews with ATON personnel at CG Headquarters, the Research and Development Center, district (oan) offices, buoy tender crews, industrial facilities, and a limited number of buoy manufacturers. The review was limited to the buoy itself and did not include the moorings, signal, etc. The buoy development projects identified included the following:

1. Articulated beacon development, 1980-present (1990)
2. Collision tolerant pile structure project, 1985-1987
3. Foam buoy development project, 1982-1988
4. 2 CPLR lighted foam buoy project, 1986-1987

5. 4x11 lighted foam buoy project, 1985-1987
6. Fast water buoy development project, 1972-1978
7. 5th and 6th class plastic buoy project, 1972-1978
8. Second class buoy project, 1972-1973
9. Lightweight lighted discrepancy buoy project, 1971-1976
10. 5x9 LPR buoy development, 1970-1972
11. CANUN buoy project, 1968-1970
12. Evaluation of plastic vs. steel for buy hulls, 1968-1970 (Booz Allen)
13. Numerical model of shallow water buoys, 1978-1981
14. Buoy motion prediction project, 1975-1976
15. Buoy hull and mooring model application study, 1970-1974
16. 8x26 BE (RR) buoy, 196 design tests, 1962
17. Exposed location buoy project, 1980-present
18. Unlighted ice buoy project, 1981-1984
19. 6x16 LI and 7x20 LI ice buoy project, 1979-1984
20. Great Lakes ice buoy demonstration project, 1973-1975
21. Wave activated turbine generator project, 1973-1977
22. Explosive embedment anchor project, 1970-1976
23. Detection of lights on rolling buoys, 1987
24. Evaluation of structures versus buoys, 1968-1970 (Booz Allen)
25. SRA servicing system study, 1968-1970 (Booz Allen)
26. Anti-fouling rubber coating for buoys, 1966-1979
27. Accordion buoy project, 1962-1964

The literature review identified several areas for further research and development efforts:

- River buoys
- Large lightweight buoys
- Articulated beacons
- Correlation of vessel size to buoy characteristics
- LNB replacement
- Measure of buoy effectiveness
- Unlighted sound buoys

The interviews suggested improvements in the following areas:

- Buoy hull design
- Construction materials
- Payload and equipment
- Improvements to existing buoys
- Standardization

In the solicitation for the study, the CG had identified the following areas that were also discussed in the report:

- Insufficient cataloging of buoy design information
- Buoy relief and maintenance cycles
- Buoy watch circles
- Buoy shape significance
- Optimal payload support
- River buoy survivability

The report included 203 references that have been included in a CG computer database for both Buoy Technology Bibliography and Buoy Technology Abstracts (Rosenblatt, 1990). That computer database is now inactive.

In a follow-on task, Dadiola, Basar, Reyling, and Walker (1991) developed recommendations for improved ATON buoys. The review of the prior material led to the identification of 57 technologies, later reduced to 54 due to overlaps. Of those, two were already under study by the CG and 21 were not buoy hull related. The study used an evaluation instrument with 31 criteria weighted using a forced choice scale totaling 100 points. Each technology was evaluated against each criterion and the weighted scores were used to determine which technologies should continued to be considered. A total of 19 (with point scores above the average) made the cut for further evaluation. The final evaluation was made using 30 year net total discounted costs (10% discount rate). Estimates of investment costs, annual servicing costs, 6 year rehabilitation costs, annual losses, and terminal values were made for the existing buoy population (1989 dollars). The key data for the economic analysis is in Table IV that shows the estimated costs for the technology as some percentage of the base. The study indicated that some of the estimates come from the detailed description of the technology, but in other case, estimates were made.

The results of the economic analysis provided a rank order for the technologies based on economic savings over the 30 year planning horizon. The highest priority item was the use of FRP and GRP materials with estimated savings in excess of $63 million. This was followed by Systems Approach to Design with estimated savings of $54 million. The study cautions that the results are dependent on the assumptions regarding savings. The study did not include any sensitivity analysis with respect to the assumed cost reductions. In addition, the results implicitly assumed that the existing system will be replaced in total by the new system. Implementation, particularly over time, is not considered and time delays are not included in the cost analysis. The specific results and recommendations are clearly assumption specific. In 1998, official guidance mandates the use of a discount rate of 7%. The lower discount rate may result in changes in the recommendations.

The focus on FRP and GRP for buoy hull material parallels a comparable recommendation made 20 years earlier by the Booz-Allen (1970a) study to replace steel buoy hulls with plastic buoy hulls. The complete Booz-Allen study included three tasks:

1. Evaluate plastic versus steel for buoys
2. Examine the tradeoffs between floating aids and fixed structures
3. Examine the servicing structure considering fixed and floating service forces, possible changes in buoy materials, and the buoy/structure mix.

The Booz-Allen evaluation of plastic buoys showed that

- Plastic buoys can be as or more effective than steel buoys as an aid
- Effective design and manufacture of plastic buoys is feasible
- Plastic hulls can be developed for buoys in virtually all environments
- Maintenance on plastic buoys would be less
- Some servicing vessels could be smaller and handling plastic buoys would be safer.

Under the then current servicing schedule (1970), there would be some savings in exposed and protected/semi-exposed environments. The total cost savings was estimated at 2% (approximately $700,000). Changing the servicing schedule and relief period resulted a 16% savings for steel buoys and a 17% savings for plastic buoys. The cost savings for plastic over steel under a revised servicing schedule was approximately $200,000. The study then considered changes to the servicing vessels and used smaller vessels where possible. Under this scenario, an additional 8% savings was realized for steel buoys (22% total), and an additional 11% savings realized for plastic buoys (28% total). The cost advantage of plastic over steel was now $1.5 million. Based on these results, the study recommended the wide use of plastic buoys (along with servicing improvements specified in Task 3).

The Booz-Allen recommendations and projections with regard to plastics have been the least thoroughly implemented of their recommendations (US Coast Guard, 1994b). SRAMA indicated that plastics have been found as effective as steel in providing a signal for unlighted and small lighted buoys. However, larger plastic lighted buoys have not been as effective, both in terms of construction and their natural motion due to the light weight. The largest plastic buoy in use is a 4.5x9 foot replacement for the 5x11 foot steel buoy. The 1983 SRA Study contains a good description of the evolution and evaluation of plastic buoys from 1968 through 1983 (US Coast Guard, 1983).

Design and manufacture of plastic buoys has not been as inexpensive as originally projected. While maintenance costs are less, the usable life of plastic buoys is still unknown, due in part to the advances in plastics. Large reductions in the size of support vessels has not been realized. SRAMA noted that other factors such as an oil recovery capability along with desirable ship's motion characteristics drove the design size for the replacement offshore and coastal buoy tenders rather than cargo or lifting capacity (US Coast Guard, 1994b). Lift capabilities for large plastic buoys will continue to be driven by the weight of the mooring and the need to use ballast for stability. The servicing force reduction that is being realized is the shift from inland tenders to buoy boats, along with an opportunity to develop an even smaller resource that may replace the 55' ANB to service plastic buoys and fixed aids.

The Booz-Allen Task 2 evaluation of replacing buoys with structures considered approximately 5,100 buoys (300 lighted and 4,800 unlighted) that were in protected/semi-exposed environments and in 20 feet or less of water (Booz-Allen, 1970b). The results of this task and related recommended changes in servicing practices have had significant results on the Coast Guard aids to navigation program. Booz-Allen observed that because structures are more effective aids to mariners than buoys, replacement could be on a better than one-to-one basis. In addition, structures could be serviced by smaller vessels and on a slightly reduced schedule than buoys. Booz-Allen concluded that life-cycle costs of structures and buoy systems were comparable when the servicing vessels are comparable, but that significant cost savings could be realized if improved servicing schedules were used for both buoys and structures. The study estimated annual savings of $10 million by the combined use of structures, plastic buoys, improved servicing schedules, and smaller servicing vessels.

Based on the recommendations in the Booz-Allen report, the Coast Guard initiated the "Buoys to Beacons" program to convert buoys in 20' of water (or less) to fixed structures. The Booz-Allen study recommended conversion of 20% of the buoys

to fixed structures; the Buoys to Beacons program estimated 10% conversion; the actual net conversion has been about 2% (US Coast Guard, 1994b). Beacons are not well-suited to areas subject to ice (e.g., First and Ninth Districts, parts of Fifth District) nor to areas characterized by deep water and rocky bottoms. In some area, such as upper San Francisco Bay, many stations that had been converted to lights have since returned to lighted buoys due to the high knockdown rate.

The change from buoys to beacons illustrated the advantage in reducing the servicing requirements and led to the development of Aids to Navigation Teams (ANTs). The development and implementation of the ANT concept has been a major factor in the reduction of servicing resources from the 1966 recommended fleet to the current service force mix. This development is discussed in detail in Section 7.0.

4.1.5 Other Aid Studies

Table 4.5 summarizes a number of R&DC studies addressing issues in aid positioning, evaluation of existing buoy tenders, and human factors in maritime navigation.

Table 4.5: Other R&DC Studies on Aids to Navigation.

R&DC No.	Date	Title
5/78	Mar 78	An Overview of Alternative Techniques for Determining Positions at Sea, with Emphasis on Applicability of Potential Use for Positioning Buoys
14/78	Jul 78	Proper Procedures for Use and Adjustment of the Survey Sextant
5/81	Apr 81	Analytical Positioning of Aids to Navigation
1/84	Feb 83	Side by Side Buoy Tender Evaluation Seakeeping and Maneuvering Comparison of USCGC Mallow (WLB 396) and SS KAIMALINO (Semi-Submersible Platform)
8/85	Dec 86	Loran-C Signal Stability Study: US West Coast
5/88	Jan 88	Technical Evaluation of U.S.C.G. 180', 157', and 133' Buoy Tenders
16/91	Jul 91	Resistance and Seakeeping Data Base for USCG 157 Ft. WLM
6/93	Feb 93	Human Factors Plan for Maritime Safety

4.2 Buoy Technology and the Effect on Buoy Tenders

Buoy tender capability requirements depend on the nature of the aids that the tender is required to service, the environment in which the aid is placed, and the location of the aid relative to the buoy tender's home port. As indicated above, the cargo and lift capacity requirements were not the determinant characteristics that dictated the design of the replacement seagoing and coastal buoy tenders. The effect of various aspects of buoy characteristics on appropriate servicing vessels is considered in many of the studies described in Section 7.0. In reviewing the requirements for the WLB/WLM acquisition, the program manager assessed the impact of technology changes on vessel requirements (US Coast Guard, 1987a). Specifically, the paper focused on plastic versus steel, buoys to beacons, and GPS satellite navigation. The paper included a good review of the plastic buoy research to date and concluded that steel buoys will still

be required in the exposed and semi-exposed environments. The buoys to beacons implementation of the Booz-Allen study was not implemented as extensively as recommended. The paper suggested that a major reason was the limited availability of the construction tenders. The paper noted that changes in the servicing interval recommended by Booz-Allen were implemented in 1974 and resulted in reducing the WLB/WLM fleet from 38/17 to 28/12 in 1987. This review did not mention the role of ANTs in this implementation. The paper concluded, citing several international authorities, that the use of satellite technology (then expecting 100 meter accuracy) will not affect the need for short range aids to navigation. Even if GPS could supplant the need for the 9 foot buoys, this would only reduce the lift capability for WLBs. Seakeeping ability would remain the same. The paper noted the ongoing conversion to solar power for buoys, but concluded that the same lift capability would be required for WLB/WLMs.

The Chief, Systems Technology Division offered some alternative considerations (US Coast Guard, 1987b). The memo reviewed the technological improvements, noting that potential changes to the configuration and deployment of some SRA systems may affect the characteristics of the required WLB/WLM capabilities. The memo noted the effect of using lightweight materials and synthetic moorings for buoys. It noted the increased reliability of buoy power systems that followed the move to solar power. It indicated that research to reduce signal power could extend the power system life and reduce the servicing frequency requirement. It reported on the Automated Aid Positioning System that may significantly increase the productivity of the tenders. The memo suggested that the articulated light may serve as a suitable replacement for many of the larger aids, reducing the lift capability if these are implemented. The memo suggested that GPS will reduce the need for some of the off shore floating aids. The memo concluded that the capabilities of the existing fleet will be required in the future, but cautioned that some changes that may affect the numbers may be appropriate. The explicit vessel capabilities for the replacement offshore and coastal buoy tenders are specified in the sponsor's requirements document (US Coast Guard, 1988).

4.3 Maintenance and System Support

Maintenance of aids is provided by servicing units for a significant amount of required maintenance. However, some essential (usually major) maintenance must be performed by other support units. Variously, this maintenance has been performed by Bases, Depots, Support Centers, and Maintenance and Logistic Commands (MLC). Additional support is provided by various other commands and staff functions at headquarters and district levels.

The best description of current maintenance requirements is included in the two part Buoy Maintenance Study (Murphy, 1993, 1995). Part I of this study involved a comprehensive review of buoy maintenance activities in Atlantic area, exclusive of the Second CG District, considering existing resources and facilities. A primary focus was on the ability of the various buoy maintenance facilities to provide adequate service to the customers (tenders). Murphy concluded that a major service problem was caused by a shortage of buoy bodies, particularly in the First District. One recommendation of the study was that other districts should send spare buoy bodies to the First District. Several recommendations involved methods for extending on-station service life and replacing aids with smaller or less complex aids. The study addressed environmental issues that may affect coatings. Another recommendation called for an information

system that includes the condition of buoys upon relief. The study included transportation data relative to delivery of aids from the maintenance facilities to the tenders. The study did not include any direct cost analysis. The results and recommendations were based on survey and interview data.

Some of the recommendations involved organizational issues, all having the goal of centralizing the management of the industrial facilities and removing industrial functions from primarily operational units (e.g., some Bases). A 1994 Focus Group addressed organizational issues (US Coast Guard, 1994a). This study examined potential organizational relationships and managerial responsibility for Bases and Support Centers. A total of five alternative organizations were considered. The reduction in staff at Industrial Support Activities (ISA) (from 1300 in 1961 to 520 in 1994) suggested that some redistribution may be appropriate. The study recommended an organizational concept that will centralize the management of all units with Industrial Support Activities (ISAs). It recommended that Office of Engineering, Logistics and Development be the Heaquarters Point of Contact for both Bases and Support Centers. Some Base industrial support activities would be transferred to Support Centers while the Group Engineering functions would remain in place. Some Bases would become Support Centers.

Part II of the Buoy Maintenance Study updated assumptions from Part I and evaluated new buoy maintenance arrangements using life-cycle cost analysis. The update indicated that the buoy body shortage has been addressed. The report noted that most of the evaluations and tests of large foam buoys have not identified good solutions. The closing of Support Center New York resulted in transferring that maintenance responsibility to South Weymouth. No specific recommendations were made for the Fifth District facilities because D5(oan) indicated that they could resolve the problems. The Florida/Gulf Coast problem included seven alternatives that were examined in a life-cycle cost analysis. The study recommended that Base Charleston and Base Mobile continue to function and that the maintenance at Base Miami, Base Mayport, and Galveston be contracted out. Appendices to the study include detailed cost data for all buoy maintenance functions, transportation, and capital improvements.

A critical support system involves personnel. The recommendations of the Booz-Allen study (1970a, 1970b, 1970c) included the implementation of ANTs as well as the reduction in other servicing resources. The study projected a reduction in the number of ATON personnel of approximately 1,700 persons in 1985 compared to the personnel required if the 1971 servicing forces were continued, a reduction of 43%. Coyle (1971) addressed personnel requirement for aids to navigation in detail. A previous 1969 study completed by Systems Development Corporation sponsored by the Office of Personnel identified training requirements for ATON that were considerably in excess of available resources. One of the keys to successful implementation of the Booz-Allen recommendations was training of personnel, particularly since more responsibility for aid maintenance was being moved down to smaller units (ANTs) with fewer experienced personnel. The current study noted that the dispersion of personnel using ANTs actually mandated an *increase* in ATON trained personnel over that required using buoy tenders prior to ANT implementation. The implication is that even though the number of personnel would decrease, training requirements would increase. SRAMA reported similar concerns about training, particularly for personnel assigned ATON responsibilities at SAR Stations, where lack of a mission specific focus has led to poor performance (US Coast Guard, 1994b). The zero-base personnel requirements study

projected 1991 aids to navigation personnel requirements based on the program manager's estimate of the fleet size and augmentation of ANTs with structural maintenance teams and boat crews (US Coast Guard, 1980). The study included significant training capability at an aggregate level.

4.4 Future Developments

There are several potential developments that could affect system performance and servicing requirements. The first possibility is the use of buoyant beacons to replace floating aids, lighted and perhaps unlighted aids. The use of such beacons should reduce the maintenance requirements, specifically the six year relief of buoy hulls. These beacons would be used in water where the depth exceeds 20', the present limit for existing construction tenders. It is estimated that a service life of 10 years between heavy lifts could be expected for buoyant beacons. Interim service would be provided by an ANT. In addition to a potential reduction in fleet requirements, this technology could impose new capability requirements. Large taut moor structures in Europe use sinkers up to 50 tons (US Coast Guard, 1994b).

Ongoing R&D efforts are examining the possibility of light sources that emit colored light directly. This could result in reducing the power required or reduce the need for a focusing lens. Ultimately, this may extend the service life of incandescent lamps in use today, resulting in an extension of the servicing interval.

A large percentage of construction tender time is spent repairing or replacing structures damaged by collisions with towboats and barges. A collision tolerant piling structure is being tested to determine if it can resist collisions with vessels. If successful, new construction requirements would be imposed, but there would also be a reduction in the required inland construction tender fleet size.

4.5 Aid Technology, Buoy Hardware, Moorings, Maintenance, Logistics, and System Support References

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5.0 SUMMARY OF STUDIES FOCUSING ON AID SYSTEM USE AND WATERWAY DESIGN

5.1 Background and Early Studies on Visual Aid Information and Use

Aids to navigation play a major role in safe usage of waterways by maritime commerce. Figure 5.1 (adapted from Armacost, 1978) illustrates the navigation subsystem that includes aids to navigation as one of its principal parts. In order to improve the safety of waterways, it is important to understand what information is provided to the mariner by aids to navigation and how that information is used with other information in a way that results in safe navigation.

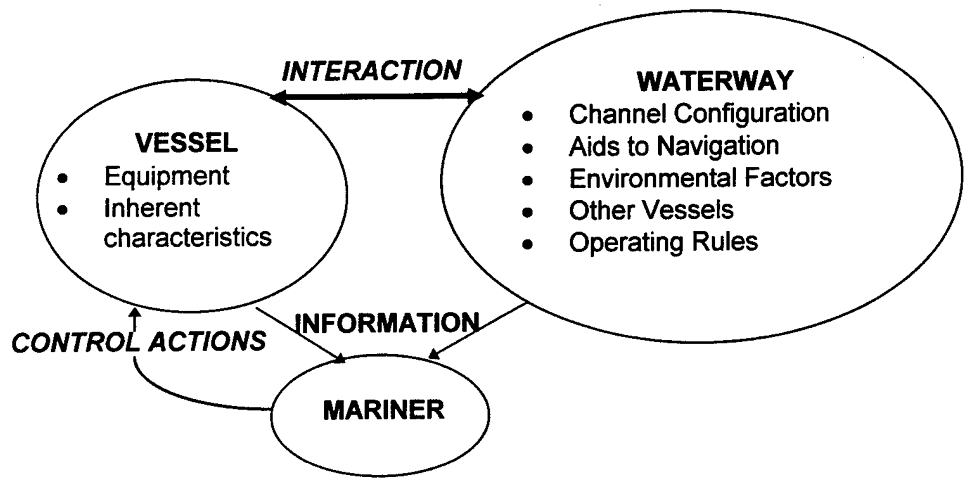

Figure 5.1. Navigation Subsystem.

The earliest Coast Guard studies addressing this issue were conducted by Bates (1972, 1974). The 1972 study involved the development of a physical Channel Lighted Buoy Model, a scale model that recreated the mariner's perspective. This is the first attempt to capture the cognitive and perceptual impact of various aid configurations. The 1974 study involved temporal and chromatic lighting of aids. The physical models, however, did not represent the mariner's use of the information provided.

In the mid-1970s, primary responsibility for waterway design rested with the US Army Corps of Engineers. The Coast Guard was tasked with the responsibility of identifying the costs of establishing and maintaining aids included in Corps of Engineers waterways projects. The aid stations were often selected by the Corps and there was little interaction to determine what the best aid configuration would be for a given waterway. In fact, the only quantitative criteria for design of aids to navigation systems that existed in 1978 were those contained in the Coast Guard Aids to Navigation Manual (CG-222) (Armacost, 1978). The stated criteria were limited, indicating that for a five foot height of eye, one should see two aids ahead (on each side during daylight), and providing an average spacing for aids in different operating environments. There were additional qualitative criteria that relied on experienced judgment to resolve such questions as gated versus staggered arrangements, or lighted versus unlighted arrangments.

The lack of quantitative standards and the inability to evaluate the performance of aids to navigation *systems* led to a major, multi-year research program to determine how aids are used, what other information is used, and what information is needed when navigating a vessel in a restricted waterway. The scope and direction of the research is indicated in Armacost (1977). The resulting Performance of Aids To Navigation Systems project used a two phase approach with three contractors (Eclectech Associates, Inc.; Science Applications, Inc.; and Systems Control, Inc.) in a Phase I "design competition." All three contractors developed a model of the mariner/pilot and the process of obtaining position information, relying variously on their own experience, data collected on board vessels, interviews, and psychophysical experiments. Based on these sources, they constructed mathematical models that used observations of the aids to provide navigational information. All three contractors included their models in a fast time simulation to examine various measures of safety and traffic facilitation based on using the model in a Monte Carlo or covariance propagation mode.

The model results by Clark et al. (1978) were validated against man-in-the-loop simulations at the Computer Aided Operations Research Facility (CAORF), the only real time ship simulator available for research. The model was used to successfully emulate mariner/vessel performance in real world conditions. The mariner's requirements for navigational information available from aids was identified and correlated with information associated with unique vessel, environmental, and visual aids to navigation system characteristics. The form and structure of a preliminary Navigation System Evaluation Model were developed, and the requirements for model completion and validation were defined. The report contained significant detail on how the navigation processes were modeled.

The Phase I effort provided an opportunity to "discover" that the Maritime Administration had undertaken a research program of "Restricted Waterway Experiments" that involved aids to navigation using the vessel simulator at the Computer Aided Operations Research Facility (CAORF) located at the National Maritime Research Center, Kings Point, NY. The initial phases of the experiment estimated an upper bound on the minimum number of aids needed for safe transit in an easy channel. Follow on work in a more difficult maneuvering situation with minimal aids proved unsafe. (Armacost, 1978). The Coast Guard joined the project to add aids and modify the channel to represent better waterway design. The results, described in Smith and Bertsche (1981a), provided additional insight for the man-in-the-loop simulations being conducted in Phase II of the Performance of Aids to Navigation study. The Phase II contract was awarded to Eclectech Associates, Inc. and the follow on research is described in the following section.

5.2 Major Studies on Visual Aid Information and Use

A series of studies to identify the effectiveness of aids to navigation in varying shiphandling and maneuvering environments was the focus of Phase II of the Performance of Aids to Navigation Systems study and follow on contracts. The various experiments addressed aspects both of visual aids as well as radionavigation aids. The principal contractor was Eclectech Associates, Inc. and its successor, Ship Analytics, Inc. The various studies involving visual aids are identified below, and provided the basis for the Waterways Design Manuals discussed in Section 5.5. The studies addressing radionavigation and electronic aids are addressed in Section 8.0.

A series of experiments were conducted over a period of about six years that provided a basis for understanding the use and effectiveness of visual aids to navigation under varying circumstances. Several studies described the assumptions and parameters for and the effectiveness of real time man-in-the-loop simulations (Bertsche and Cook, 1979; Smith, Bertsche, and Schroeder, 1980; Smith, Bertsche, and Schroeder, 1981). The principal measure of effectiveness/performance in these evaluations involved the cross-track deviation and the computed risk of grounding during the specified passage. Grounding was defined as any part of the vessel passing over the edge of the marked channel.

The various simulator studies involving different visual aid configurations are indicated below with the principal topics of the experiments.

- CAORF experiment--Smith and Bertsche (1981a)
  Principal topics: Turn configuration; aid arrangements; environment
- Channel width--Smith and Bertsche (1981b)
  Principal topics: Channel width; aid arrangements
- Ship characteristics and related variables--Bertsche, Atkins, and Smith (1981)
  Principal topics: Ship size; speed
- One-side channel markings--Marino, Smith, and Bertsche (1981a)
  Principal topics: Aid arrangements; visibility
- Range light characteristics-- Marino, Smith, and Bertsche (1981b)
  Principal topics: Range sensitivity; turn angle
- Validation-- Smith, Marino, Multer, and Moynehan (1984)
  Principal topics: Baltimore approach; ship size
- Turn lighting--Smith, Multer, and Schroeder (1983); Smith and Schroeder (1983)
  Principal topics: Turn light rhythms; aid arrangements; ship size
- Short range aids with radar reflectors--Multer and Smith (1983b)
  Principal topics: Aid arrangements; visibility; ship size
- Varied shiphandling conditions--Marino, Smith, and Moynehan (1984)
  Principal topics: Aid arrangements; speed; ship size; environment
- Aids to navigation and meeting traffic--Multer and Smith (1983a); Moynehan and Smith (1985); Schroeder, Smith, and Moynehan (1985)
  Principal topics: Meeting traffic; day/night; ship size

The results of these experiments led to the preparation of aids to navigation systems waterway design manuals. The first draft appeared in 1982 (Bertsche, Smith, and Marino, 1982) and the revised manual in 1985 (Smith, Marino, and Multer, 1985). The preceding experiments only used aids with no landmass references--a blank screen approach. Additionally, the buoys did not move--they were actually fixed exactly on station. Brown, Smith, and Forstmeier (1988) conducted an experiment that included landmass (navigation targets of opportunity) and found that aids to navigation are in fact more effective in typical visual surroundings than they are with no other objects in the scene. It was found that the amount of benefit associated with the visual scene was influenced by a variety of factors including the density of objects in the scene and the distance of objects from the waterway. Brown, Smith, and Conway (1988) allowed the buoy positions to vary according to a particular probability distribution and evaluated the effects on performance of buoy excursions from their assigned positions. The *distance*

of buoy excursion had non-significant, but systematic effects on waterway performance and risk. The *direction* of current and buoy excursion had major effects on shiphandling, waterway performance, and risk. Although the report concludes that floating aids do decrease performance, or increase risk, compared to fixed aids, this difference has little consequence with respect to the general-purpose design and evaluation procedures of the Systems Design Manual. A final experiment examined ship inherent controllability and found that performance was sensitive to these controllability indices (Smith, Mazurkiewicz, and Brown, 1990). Mazurkiewicz and Smith (1991) developed a series of equations that can be used to adjust risk factors based on controllability indices. These results will be used in computing the Relative Risk Factor (RRF).

5.3 Studies Related to Models of Navigation

All of the simulator models incorporate some hydrodynamic model of the vessel. In the experiments described in the previous section, the navigation information from the aid system was obtained and incorporated through the man-in-the-loop. Clark et al. (1978) developed an analytic model for capturing aid information and using that in a fast time simulation. Drijfhout van Hoof (1982) has developed numerous perceptual and analytic relationships from visual aids that could be used to develop an analytic model to be incorporated in a simulation. Hwang (1985) developed an autopilot for the CAORF simulation, but it is not clear how the "autopilot" obtains position information and the develop appropriate course corrections. Kaufman (1985) used these results in a compressed time simulation to evaluate channel designs for the Panama Canal.

No recent studies have been identified that incorporate a modeled navigator that would then be used in a fast time (compressed time) simulation to evaluate alternative aid system arrangements.

5.4 Studies Related to Performance of Aid Systems and Waterway Design

5.4.1 General Waterways Studies

From a waterways management perspective, a number of studies attempted to address the needs of users and interventions in a broad sense. The Port Needs Study focused on navigational risk in 23 ports and assessed the benefits and costs of potential Coast Guard Vessel Traffic Services (Volpe National Transportation Systems Center, 1991). The role of aids to navigation was not addressed. The National Research Council (1996) reviewed the VTS-2000 program considering public/private sector roles, need for new or improved waterways management services, feasibility and implementation of VTS and other services, identification of beneficiaries of those services, and available funding methods. The study concluded that the technology to improve navigation safety was available, but the impediments involved funding and institutional issues. The study concluded that the existing Coast Guard-operated VTS systems are well-managed and make a significant contribution to port safety, although no quantitative data were found to substantiate improvements to safety and efficiency. The study recommended that the Coast Guard revisit the needs analysis for VTS and pursue public/private partnerships to establish baseline systems in critical areas.

Brown, Corey, and Blythe (1995) identified 586 waterways management responsibilities attributed to 99 different organizational elements involving the Coast

Guard, Army Corps of Engineers, Environmental Protection Agency, and various State Agencies. The analysis considered 497 "critical" waterways. Maio, Nabrynski, and Long (1995) defined initial categories of waterway users and their quantifiable attributes -- all types and sizes of water vehicles used to transport people or goods in commerce, and those used recreationally or in performing government functions. The study identified existing and potential sources of data for these attributes, defining those that must be quantified to support navigational risk assessment, measurement of effectiveness of Coast Guard aids and services, and the estimation of the monetary benefits of proposed changes. The Volpe National Transportation Systems Center (1996) defined waterway users by navigational requirements and to select particular user groups for in-depth study. ATON are broadly defined and operators are characterized by their navigational environments, skills, and navigational equipment. The study was intended to identify what users actually use particular types of ATON or perceive that such aids are necessary. The results are based on face-to-face and telephone interviews of representatives of Boat/US, USCG 1st District staff, and interviews with more than 20 experienced mariners who represent various categories. The report used an index to rank operators in two categories: vessel operations and navigational capability, and profile the operator dependence on each type of aid. The discussion specifically addressed recreational boaters, smaller coastal passenger boat operators, and the tug-barge trade, but suggested that deep draft vessel masters do not be considered as a group because their dependence on ATON is counterbalanced by the fact that they must carry a pilot and are under a legal mandate to be equipped with navigation systems and crew trained to operate them. The study did not attempt to identify how the various ATON are used or how they interact or substitute for other aids.

5.4.2 Waterway Design Studies

As discussed in Section 5.3, the results of the various simulator experiments led to the preparation of aids to navigation systems waterway design manuals. The first draft appeared in 1982 (Bertsche, Smith, and Marino, 1982), and after additional experiments, the "final" manual was published in 1985 (Smith, Marino, and Multer, 1985). The principal measure of effectiveness/performance in these evaluations involved the cross-track deviation and the computed risk of grounding during the specified passage. Grounding was defined as any part of the vessel passing over the edge of the marked channel. This approach led to the development of a Relative Risk Factor (RRF) that was dependent on the channel design, aid arrangements, environmental conditions, and the size and speed of the largest ships using the waterway. The RRF provided a quantitative measure for comparing alternative waterway designs for a particular waterway.

Before publishing the 1985 version of the manual, Marino, Moynehan, and Smith (1985) experimentally tested the draft manual's guidelines for evaluation and design of aids to navigation systems in restricted waterways. The Upper Narragansett Bay near Providence, Rhode Island, was the channel in which the draft manual's recommendations were implemented. Data was primarily collected at sea in both the original and modified channel. The at-sea data collection electronically tracked 30,000 DWT tankers inbound in the Upper Narragansett Bay. Data was also collected on the marine simulator developed for the project. The results of the at-sea implementation verified the recommendations of the draft manual, indicating that the manual and the basic assumptions built into it are sound. Based on the implementation experience, the final design manual should be more flexible, enabling the user to adapt the guidelines to

unique conditions, and should be less conservative and more accepting of a variety of channel markings.

Following additional experimentation involving landmass, errors in aid positions, and ship controllability factors, a revised Waterways Design Manual was issued in 1992 (Smith, 1992). This revision of the Waterways Design Manual is the result of over 13 years of man-in-the-loop simulator based research considering ship controllability and aids to navigation. This manual provides systems design guidelines that will permit a user to make a meaningful risk assessment of alternative waterway system designs for a given waterway. The manual and software guide the user through an evaluation process for a subject waterway. The general approach is, first, to select a "design vessel" to represent the traffic in a waterway and to divide the waterway into "regions" that will enclose the distance needed by this vessel to perform each of the maneuvers that comprise a transit. Conditions of the transit, including the configurations of the waterway, the short range aids to navigation, and the environmental conditions, are specified as inputs to the program. Based on the input, the program provides a "relative risk factor" (RRF) for each region of the waterway. These values can be used to compare risk in regions along a waterway, or to compare risk under alternative SRA conditions or under alternative conditions. It is emphasized that this is a risk *assessment* tool.

The SRAMA study (US Coast Guard, 1994b) indicated that the RRF has limited applicability. The study reviewed the 1985 version and noted that natural landmarks were not included, a shortcoming that was overcome by subsequent testing and included in the 1992 version. A remaining shortcoming is that the design manual does not integrate electronic navigation with visual navigation. SRAMA notes that the methodology applies only to dredged channels. The methodology applies only to the largest waterway user and the results were developed using oceangoing vessels, questioning its applicability to towboats and other small vessels. Finally, SRAMA notes that RRF is intended for comparison of alternatives and does not predict the actual probability of grounding. SRAMA emphasizes that there is no solid basis for estimating the absolute risk in a particular waterway. The SRAMA evaluation did not consider the controllability factors included in the 1992 version that make the results applicable to a wide range of vessels. It is unlikely that this would extend to towboats with a towed barge. The SRAMA evaluation is generally consistent with the stated limitations of the design manual. The design manual does provide the ability to evaluate a waterway for various users and select a design that meets their needs.

5.4.3 Risk Assessment Studies

Risk is an integral part of the focus of the waterway design experiments and the design manuals described above. In the Waterway Design Manual, it is emphasized that the RRF based on probabilities of groundings is a *relative* measure. Reik and Hargis (1983) described a comprehensive approach to marine risk management developed by MARAD in the face of pressures on port traffic by larger and more cost effective ships. (The paper noted that the Coast Guard was on public record indicating that a probabilisitc safety analysis is not a sufficient basis for the specification of maritime safety procedures.) To accommodate the human factor, MARAD used its operational ship's simulator at CAORF as its primary analytical tool in face of the mathematical intractability of human performance modeling. The approach involved describing risk identification and mitigation efforts that can be used in a relative sense to

order different situations/consequences as to relative risk and relative cost/benefits. Several analytical risk analysis techniques other than simulation were used as a form of supplemental analysis. The methodology involved identifying a hierarchy of risk categories appropriate to the situation under evaluation. The methodologies included: personnel and public risk exposure analysis, simulation (either fast-time simulations and/or real-time man-in-the-loop simulations), casualty analysis, safeguard analysis, salvage analysis, and environmental effects analysis. The paper described the application of the methodology to the Santa Barbara Channel and then proposed its application to the Texas coastal area and the Lower Mississippi River.

The Coast Guard established a Waterways Analysis and Management System (WAMS) that requires a periodic review of critical waterways (initially, every three years; now, every five years). This is a detailed multidimensional review that includes all users of the waterway. The basic guidance for WAMS and various reports is included in the Aids to Navigation Administration Manual (COMDTINST M16500.7). The National Aids to Navigation School has prepared a Completion Guide for WAMS studies (US Coast Guard, 1995). This document is designed to provide field units and District (oan) with a step by step guide to completing a Waterways Analysis and Management System (WAMS) report. The guide provides helpful hints on how to accomplish the various tasks. Although the step by step intent should be reflected in a corresponding sequence in the guide, there are clearly places where some feedback and iteration will be required. The guide identifies a number of areas to be examined, but does not give specific guidance as to how that is to take place, or what kind of evaluation is to be made. While the guide is probably very useful, it lacks clearly defined objectives for a WAMS report and no overall organization of a WAMS evaluation. If a primary objective is to evaluate the adequacy of the *system* of aids to navigation in the waterway, the objective will be missed because there is no focus on a systems view. The justification for computing the RRF is very strained. The guide could benefit from a review taken from a systems perspective by someone not familiar with the WAMS process.

Casey, Watros, and Hall (1995) identified primary navigational risk assessment methodologies, models, procedures, and practices currently used by the Coast Guard. The report analyzed the efficacy of the risk assessment tools and methodologies, including those utilized in making decisions on resource allocation within the Coast Guard, and identified potential improvements to Coast Guard risk assessment capabilities with respect to current and future risk assessment needs. Specific recommendations for research tasks enhancing current and future risk assessment needs were given. The report noted that there is no standard definition of risk assessment in the Coast Guard and recommended research to develop a quantitative risk assessment methodology, a comprehensive waterway risk model, and a resource allocation model

5.4.4 Benefit Assessment Studies

The attempt to assess the costs and benefits associated with aids to navigation have a long history, despite the fact that under the existing statutory authority, the aids to navigation program is not required to show an attractive cost/benefit analysis (US Coast Guard, 1994b). However, the SRAMA study emphasized that it would be desirable to do so from a management perspective. The first study to explicitly address benefits was conducted by Geonautics, Inc. in 1969. This study attempted to identify various systems of aids that would satisfy the users of ATON systems. The report

included a benefit methodology that was developed at a very general level to measure the value of the existing system and the value of an "improved" system. Cohen, Steinberg, and Schofer (1971) adapted this benefit methodology and applied it to evaluate existing and improved ATON systems in 43 US ports and waterways.

Various other studies described elsewhere in this report include some sort of benefits assessment (e.g., Reik and Hargis, 1983; Volpe National Transportation Systems Center, 1991; National Research Council, 1996). Greenberg, Ulvila, Marvin, Clark, and Stanley (1986) documented the first phase of a research effort designed to develop a decision model (or set of models) capable of supporting the resource management activities of the Coast Guard's short range aids to navigation program. The purpose of this part of the study was to develop measures of effectiveness for program activities that would then be used in the development of Resource Management Tool (RMT). The report included a brief review of related ATON analyses and their value in developing the RMT. The study included the results of meetings with various user groups that led to the development of a long list of potential measures of effectiveness. The study refined and condensed the list that resulted in a benefits hierarchy and a cost hierarchy, both of which contained several levels of attributes. The benefits hierarchy included safety (avoidance of accidents), timeliness (avoidance of delays) and other benefits (e.g., mariner interests, CG interest, other government interests, and public interests). The cost hierarchy considered both CG costs and other federal government costs. A weighting approach was then used to develop weights for the lowest level attributes. Various resource allocation alternatives could then be compared on the several attributes and a resulting weight or value computed for each alternative that indicates the ranking of the alternatives. The report included several appendices on Multiattribute Utility Theory and several decision analysis approaches. In this approach, the weighting aggregation overlooks the bias introduced by the uneven structure of the hierarchies. Ratio comparisons are not made directly.

This task was the first of nine planned to be studied over a five year period. Following submission of this report, the project was discontinued (US Coast Guard, 1994b). The SRAMA study noted that the lesson learned from this project was that quantitative measures are difficult to develop. In particular, this approach emphasized the use of expected benefits and costs. Events such as groundings are rare, and even if the probabilities could be estimated accurately, slight improvements would not result in significant expected benefits. Because of the difficulty in estimating the probabilities of these "rare" events, pursuing this approach was not supported. SRAMA noted that factors such as human safety, enhanced timeliness (e.g., enabling night navigation) or other benefits might tip the scale in a full analysis of a real problem. The need for further analysis in this area was indicated by Casey, Watros, and Hall (1995) as described previously.

5.4.5 System Effectiveness Studies

System effectiveness is an implicit consideration in examining various benefit and waterway design studies. The need for a system effectiveness measure was identified in the operational design tasks for aids to navigation by Armacost (1977). The follow-on simulator experiments to estimate what and how navigation information is used, the efforts to improve the positioning of aids, and the system reliability analyses provide the tools to assess system effectiveness. That system effectiveness measure remains an elusive goal twenty years later.

Winkellar, Watros, and Weber (1995) explored the use of performance measures and a performance measurement system as a framework for measuring the effectiveness of improvement efforts. The report provided background on the definition of performance measures and methodologies for developing such measures; reviewed some examples of "best practices" in performance measurement; described current Coast Guard practices for measuring the performance of waterways management; and recommended specific research tasks.

There are no recent efforts to assess the effectiveness of aids to navigation systems. As many of the studies in this section indicate, the focus appropriately is on waterway effectiveness, in which aids to navigation play an important role along with other factors as illustrated in Figure 5.1. The Volpe National Transportation Systems Center (1996a) is currently involved in developing a Waterways Evaluation Tool (WET) in response to the identified need for decision support tools to assist in waterways management. WET is intended to facilitate the comprehensive evaluation of the performance of waterways. As noted in Section 5.4.3, WAMS requires a periodic analysis/redesign of a waterway. However, it is not done in a comprehensive and consistent manner among districts and over time. Additionally, the WAMS process is very resource intensive. The purpose of WET is to provide a mechanism for consistent and more comprehensive analysis with a requirement for fewer resources to complete the evaluation. The functional requirements report suggests that the resulting product will be useful for selecting and funding AC&I projects nationwide.

The report described the approach that will be used in WET and provided some examples. The approach primarily involves the use of value trees to evaluate both the performance and importance of waterways. With these two measures, a Significant Performance Index is computed that provides a baseline measure of performance with respect to the most important function(s) of the waterway. Separate value trees will be developed for each of five Coast Guard strategic goals. The value trees use both objective and subjective scoring procedures. The subjective scoring typically involves a 1 - 5 scale. Weights for the various elements are provided for general waterways, but certain users may specify particular weights for given waterways. For most performance elements, an additive approach is used to aggregate the scores. The functional requirements report only contains partial information on the various value trees.

The proposed methodology using value trees makes some unstated assumptions about the value functions (e.g., risk status, mutual preferential independence). In addition, the method by which the weights for the various elements and sub-elements are obtained for an individual waterway is not described in the functional requirement. The general waterway weights were developed by the Technical Advisory Team using Groupware (method not specified). The issue of interpersonal value/utility comparisons has not been addressed. The report would lead one to believe that evaluations of different waterways by different users can lead to meaningful comparative results. This is one of the remaining unresolved issues in decision theory and stands as a roadblock in the application of WET. With respect to SRA and RA, their location in the mobility value tree seems to indicate a diluted importance (simply from the structure of the tree) for those elements. While WAMS may not be giving a good systems analysis of the waterway, it is not clear that WET as proposed in this report will either.

5.4.6 Other Studies

The use and effectiveness of aids to navigation depend critically on how the mariner obtains and processes the information from the aids. The cognitive and perceptual aspects are critical. The various man-in-the-loop simulator experiments captured the effects of those processes implicitly, but did not explicitly address the elements of these cognitive and perceptual models of human behavior. The simulation model by Clark et al. (1978) and the text by Drijfhout van Hoof (1982) created analytic representations of information based on a perception of aid positions.

Sanquist, Lee, and Rothblum (1994) presented an overview of four different, but complementary methodologies being developed to assess how a given automated system changes shipboard tasks and the knowledge and skills required of the crew. The report focused on one of these methods, a powerful new application of cognitive analysis. Cognitive analysis identifies the mental demands (e.g., visual detection, computation, and memory) placed on the mariner while performing shipboard tasks. A comparison of the mental demands associated with manual versus automated tasks can highlight differences in the knowledge, skills, and abilities required to perform the tasks. Thus, cognitive analysis identifies changes which may be needed in training and licensing/certification as a result of shipboard automation. The body of the report is a technical documentation of the cognitive analysis method. This approach may have potential for identifying the cognitive load associated with the process of navigation using different aid arrangements and possibly for integrating visual and electronic aid processing.

Lee and Sanquist (1993a, 1993b) summarized a collection of papers related to the application of human factors in the maritime industry. These papers describe human factors problems in the maritime industry, research designed to offer solutions, and research in other domains that may apply to these and other potential problems encountered in the maritime industry. The papers are grouped in six areas, each dealing with a particular area of interest: automation, fatigue/incapacitation, manning, navigation, organizational factors, and training. An annotated bibliography includes a summary of each paper that includes the complete citation, a synopsis of the methodology used, issues addressed, principal findings, and any technical problems or deficiencies.

The availability of information for waterways management continues to be a critical factor in all aspects of waterways issues. Heerlein (1996) identified and cataloged present Coast Guard waterways data. The identified systems were categorized and described in terms of their content, capability, and access. The following systems were identified.

Category 1--active Coast Guard systems with essential waterways data

- Light List--annual 7 volume publication. Electronic read-only through DMA's NAVINFONET.
- Waterways Analysis and Management System (WAMS)--paper reports evaluating individual waterways. Available in district offices.
- Automated Relative Risk Factor (ARRF)--computer program to compute the RRF used in evaluating waterway safety.

- Aids to Navigation Information System (ATONIS)--relational database recording features of aids to navigation and servicing. Separate data bases maintained in district offices.
- Laptop Automated Aid Positioning System (LAAPS)--real-time software application design to position floating aids to navigation. Operates in a laptop environment.
- Navigation Information Service (NIS)--public information service involving radionavigation data associated with GPS, DGPS, OMEGA, and LORAN. Available through an electronic bulletin board and WWW.
- Geographic Display Operations Computer (GDOC)--software application that displays maps and nautical charts used primarily at operations centers to plan SAR operations.
- Marine Safety Information System (MSIS)--historical records of marine inspection activity and incidents with over 250 "products" prepared for various users. Various subsystems perform specific analyses.
- Spill Planning Exercise And Response System (SPEARS)--provides centralized location for accessing data necessary for spill response. Implemented on Apple MacIntosh computers at MSOs and NSF.

Category 2--planned Coast Guard systems with potential waterways data

- Marine Safety Network (MSN)/Ports and Waterways Management Information System (PAWMIS)/Merchant Mariner Documentation System (MMDOC)
- Marine Information, Safety and Law Enforcement (MISLE)/Marine Safety Network (MSN)/Vessel Identification System (VIDS)
- Operations Information System (OIS)
- VTS-Upgrade/Automated Dependent Surveillance (ADS)/VTS-2000
- Waterways and Navigation Data Services (WANDS)/ Local Notices to Mariners (LNM) Automate
- Bridge Information Systems (BRIDGIS)

Category 3--other Coast Guard systems with some data relevant to waterways

- Automated Mutual-Assistance Vessel Rescue System (AMVERS)
- Search and Rescue Information System (SARMIS)
- Law Enforcement Information System II (LEIS II)

Category 4--other systems (non-Coast Guard)

- Internet/WWW
- DOT Bureau of Transportation Statistics
- NOAA
- US Army Corps of Engineers
- MARAD
- Lockheed Martin MTM/Halcrow-Integraph PIMS

The study revealed that most data cannot be easily accessed because it is stored locally at unit and district offices. Redundant data were found in some of the systems. The report identifies developments such as moving to an open architecture that has the potential for making data more accessible. The role of the Internet is also explored.

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6.0 SUMMARY OF STUDIES FOCUSING ON POSITIONING

6.1 Background

A major component in visual system effectiveness involves the accurate positioning of aids. The desired location of an aid station is determined based on the waterway design. Traditionally, horizontal sextant angles had been used for aid positioning. It is well known that the use of horizontal sextant angles can provide a very accurate position when the reference objects are selected properly. However, errors in the process may result in substantial degradation of the information provide by the aid. With advances in radionavigation accuracy, electronic positioning has developed to a level of sophistication that it may reliably be used to position aids.

Couchman (1978) cataloged and evaluated various field survey techniques of position determination, whether presently in use or in development, with particular emphasis on the general capabilities, limitations, and application of the individual techniques for use in positioning buoys. The results of the evaluation indicated that no single method can be used to satisfy the varied buoy placement scenarios. Instead, a combination of methods would be most appropriate. Furthermore, no single combined-methods system would fit all applications unless it consisted of an all-encompassing set of equipments and procedures; an impractical solution. Laser rangefinder, precision gyrocompass, radiodetermination, and satellite methods are considered to have applicability to buoy placement operations, either as stand-alone or for incorporation with a multi-sensor system. Inertial guidance and underwater acoustic methods are not considered to have practical application. While radionavigation accuracy has advanced considerably since 1978, as has visual positioning, the basic conclusion that a combination of methods is required for reliable positioning probably remains valid in 1998.

6.2 Studies Related to Visual Positioning Methods

Armacost (1978) described the role of the Aids to Navigation Positioning Project (ANPP) in developing and implementing improved positioning procedures and monitoring a large research and development program described in the *Technical Development Plan for the Navaid Placement Project*. The ANPP focused on improving the use of horizontal sextant angles by minimizing the errors and providing revised quantitative standards. The major sources of error were the paper charts and the use of a three-arm protractor which often resulted in selecting a common center object for the two angles. The resulting two lines of position may not yield a strong fix. The ANPP solution was to pre-compute the sextant angles that would eliminate the chart-related errors and permit the selection of objects whose lines of position result in a strong fix. Each aid station was examined and a gradient diagram prepared that would assist the conning officer in approaching the aid station.

The R&D tasks involved examination of the total error budget in positions, evaluation of electronic methods for positioning, evaluation of alternative methods for auditing the positions of aids, evaluation of improved moorings, and development of improved training programs for improved positioning methods. For example, Millbach (1980) developed a computer model written to simulate errors associated with the Coast Guard aids to navigation positioning process with emphasis placed on finding average

effects of errors in the system. A mathematical expectation approach was used to model random system elements. The model routines were designed to study specific positioning situations, or, by use of Monte Carlo methods, a variety of situations as a group. The model was designed for use in planning within the aid positioning macrostructure. For planning purposes, the probability that the resulting position lies within a specific circular region is a meaningful measure of positioning success. Table 4.5 includes several studies (1978-1981) on positioning aids, including other analytical evaluations. The efforts from the ANPP and related studies led to the adoption of improved positioning procedures that have been incorporated in the Aids to Navigation Manual – Positioning (COMDTINST 16500.1B). Moreover, the procedures have been programmed in the Laptop Automated Aid Positioning System (LAAPS) currently in use by servicing forces.

6.3 Studies Related to Auditing Aid Positions

The traditional method for auditing the positions of aids to navigation has been to rely on the observations of mariners. All Coast Guard units underway are required to observe aids and report any obvious discrepancies in aid positions. Whenever there is a marine incident, operating procedures require that aid positions be verified. Finding effective systems to conduct that auditing has been another program objective.

Several studies examined alternative methods for auditing positions of aids to navigation. Some were considered for regular use and others on an as needed basis. Giovane (1977a) evaluated aerial imaging systems capable of establishing the positions of aids to navigation to within 30 meters within 48 hours following adverse weather conditions such as ice or storm. A scenario area (400 km by 3 km) was created to simulate a region affected by such environmental conditions. The study considered aerial photographs, side-looking airborne radar, and visual observations from aircraft. It was concluded that none systems currently available to the Coast Guard to achieve aerial semi-precise survey of aids to navigation.

In a second study, Giovane (1977b) investigated the feasibility of using aerial imaging techniques for verifying precisely the positions of aids to navigation was conducted. It was determined that such a method is technically feasible using cartographic aerial photography and precise photogrammetric data reduction. However, such a system would be impractical and expensive for Coast Guard use on a routine basis.

Bauman, Waelbrock, and Giovane (1978) examined the possibility of using VTS radar and/or Low Light Level Television (LLLTV) to conduct visual audits of buoy positions in a Vessel Traffic Service area. Buoy position audit using LLLTV does not appear feasible. Only general aid condition information is available. LLLTV does not produce adequate position information. Buoy position visual auditing using VTS radar could be feasible if certain improvements are made in the information display and interpretation areas. However, Coast Guard VTS units do not have the resources to conduct an aggressive, accurate visual buoy position audit program.

6.4 Studies Related to Electronic Positioning Methods

Viable electronic positioning systems appeared with the development of the Differential Global Positioning System (DGPS). Krammes and Crowell (1990) described

the evaluation of DGPS (implemented in LAAPS) as a primary means for positioning aids. The evaluation involved positioning 29 buoys in Narragansett Bay and the results strongly supported using DGPS as a replacement for horizontal sextant angles. Notable is the reported "smoothness" of the display using DGPS due to the inherent system and accuracy with DGPS.

Spalding, Flynn, and van Diggelen (1993) and Spalding, Flynn, Milne, and van Diggelen (1994) evaluated a prototype Receiver Autonomous Integrity Monitor (RAIM) algorithm named NAVSAFE developed by NAVSYS, Corp. that detects position errors that exceed the user's desired level and detects when the probability of a false alarm exceeds the user's desired level. The evaluation led to the development of a NavPlan module that permits the planning of ATON work to coincide with good satellite geometry. The evaluation supports the development and use of RAIM in conjunction with DGPS for positioning aids, providing a measure of the quality of information and also provides documentation of the aid position as a legal document. The recommendations regarding data recording have been implemented on aid servicing units. The actual RAIM algorithms have not been implemented on the units. In theory, the recorded data can be processed with a post-mission RAIM program.

The use of DGPS for aid positioning requires that the Coast Guard provide the DGPS service in the area. There are some areas where there are no plans to provide DGPS. Spalding and van Diggelen (1995) analyzed the potential use of GPS+GLONASS (GNSS) receivers to provide position information of sufficient accuracy to permit positioning of aids to navigation in those areas where the Coast Guard does not maintain a Differential GPS capability. The data presented demonstrates that this technology can meet Coast Guard requirements for buoy positioning. Finally, the paper described a prototype software for positioning buoys using a GPS+GLONASS receiver.

6.5 Positioning References

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7.0 SUMMARY OF STUDIES FOCUSING ON SERVICE FORCE MIX

7.1 Background

In analyzing aids to navigation systems, it is necessary to consider effectiveness issues and to consider efficiency issues. Effectiveness is related to providing appropriate aids to enable the mariner to obtain adequate, timely, and reliable information that will be of use in navigating the ship. Alternative aid mixes may provide equally effective systems. Efficiency is concerned with the cost of providing an effective system. The system cost includes not only the capital cost and direct operating cost of the aid (e.g., paint, lamps, batteries), but also the capital and operating costs of the units that establish and maintain the individual aids. For a given set of aids, there are alternative ways of establishing and maintaining aids. The combination of operational units used to implement those alternatives has been called the service force mix.

There have been considerable efforts to identify the appropriate service force mix over the years. The different nature of the aid systems and operating environments in different parts of the country have enabled those who have studied the problem to decompose it into roughly independent elements. For example, the aid system on the western river system operates independently, as does the aid system on the Great Lakes. Along the Pacific coast, few aids and long distances in exposed environments are the norm. Along the Gulf Coast and southeast US, shallow water creates more opportunities for fixed aids and the construction tender fleet can be isolated for analysis. The apparent independence, however, is slightly misleading because all of the different elements are interrelated. Different studies have taken different approaches as illustrated in the following sections.

7.2 Booz-Allen and Early Service Force Mix Studies

7.2.1 Booz-Allen Studies

In providing the background for aids to navigation analyses in Section 3.0, it was noted that following the GAO audit of the First District aids to navigation operations and the transfer of the Coast Guard to DOT, an issue paper that examined buoy tender utilization identified the need for a Coast Guard wide examination of servicing forces (US Coast Guard, 1967). The Coast Guard formed a National Navigation Planning Staff that managed the Booz-Allen study that was completed in 1970. The Booz-Allen study is a landmark in aids to navigation planning since it represented a departure from the incremental efforts that had preceded it. Booz-Allen took a systems view of aids to navigation and developed an integrated proposal for the service force mix. The Booz-Allen study involved three tasks:

1. Evaluate plastic versus steel for buoys
2. Examine the tradeoffs between floating aids and fixed structures
3. Examine the servicing structure considering fixed and floating service forces, possible changes in buoy materials, and the buoy/structure mix.

The first two tasks were technically narrow, but they provided the possibility of a different aid mix for which the servicing forces would be configured. The results of Tasks 1 and 2 (Booz-Allen, 1970a, 1970b) are discussed in Section 4.1.4 above. The Task 3 recommendations resulted in a revised service force mix (Booz-Allen, 1970c).

The recommendations included the recommendations from Tasks 1 and 2 that called for increased use of plastic buoys and converting about 5,100 buoys to structures. A key recommendation involved reducing the servicing frequency for all types of aids, and assigning dual responsibility for aid maintenance. A new service element was proposed: the Aids to Navigation Team (ANT) that would be equipped with special Aids to Navigation Boats (ANB) or trailerable ANBs (TANB). Booz-Allen identified a complete mix of shore facilities that would be required to support the servicing effort.

The major cost reduction came with reducing the number of offshore and inshore buoy tenders associated with changes in servicing schedules and the use of dual responsibility for aids. Booz-Allen suggested two reduced service schedules. Under the 1971 servicing policy, WLBs made an average of 3.3 visits per year for scheduled checks (1.0 visit) and service (2.0 visits) as well as unscheduled service (0.3 visits). Under alternative 2 (same frequency but reassigned responsibility), an ANT would be responsible for the scheduled check (1.0 visit) and unscheduled service (0.3 visits) and the Offshore Buoy Tender (OBT) would be responsible for the scheduled service (1.0 visit). Under Alternative 3, the scheduled check changes to 0.5 visits per year and the scheduled service goes to 0.5 visits per year. There were 38 WLBs (Alternative 1) in 1971 and a total of 45 would be required in 1985 given the projected aid growth. For the projected 1985 aid population, under Alternative 2, the total requirement was reduced to 24 and under Alternative 3, the OBT requirement was reduced to 17. Similar analyses reduced the 1971 WLM/WLI requirement from 38 (46 in 1985) to 22 (Alternative 2 servicing) or 18 (Alternative 1 servicing). The construction tenders remained constant at 10. The river tenders were reduced from 25 (29 in 1985) to 9 (Alternative 2) or 6 (Alternative 3). River ANTs were used extensively to supplement the river tenders. The life-cycle operating cost analyses showed reduction of 30 to 40% over Alternative 1. The new servicing alternative required a capital investment to establish the ANT facilities and boats as well as conduct a modernization and acquisition program for new tenders.

The analysis concluded that the cumulative operating costs savings over the next few years would be equal to twice the amount needed to construct all of the vessels for the proposed system. Booz-Allen emphasized the need for an accurate and up-to-date information system (SANDS) for system management, and a comprehensive R&D effort to improve signal hardware reliability and effectiveness. A final recommendation involved training policies. The ANTs would be specialized units that would require adequate training since they would be replacing the better trained personnel on buoy tenders. Although there were no ANTs in 1970, several shore stations, primarily SAR stations, did have some aids to navigation responsibilities. Aids to navigation training for those units was weak and the lack of a mission focus led to poor performance (US Coast Guard, 1994b). The study recommended the development of an aids to navigation training team as part of the training emphasis.

The Booz-Allen analysis was comprehensive in examining all aspects of the ATON operating system. The final report documents the numbers of units and the service policies that are recommended. However, it does not document what type of analysis was used to determine how many buoy tenders of each type were required in each district. It appears that some assumptions were made about the length of coastline that could be assigned, along with aid density and some estimates of service time and enroute times for given ship speeds. A simple deterministic model was probably used to estimate the maximum coastline/density combination that could be serviced within given workload parameters.

7.2.2 ANT Studies

With the completion of the Booz-Allen study, the National Navigation Planning staff was disestablished and responsibility for implementation of the Booz-Allen recommendations was assigned to the Aids to Navigation Division. In order to test the viability of ANTs, ANTEVALUNIT New Haven was established. Based on that successful experience(resulting in the decommissioning of a buoy tender), a program for establishing ANTs was initiated in 1973. There do not appear to be any studies or analyses clearly delineating the scope and functions of ANTs. The locations were based largely on District input at the conclusion of the Booz-Allen study (Armacost, 1977). ANTs were provided with high speed Aids to Navigation Boats (ANB) with a limited lift capability (anticipating heavy use of plastic buoys). This design failed to account for the continued need to use sinkers that require weight handling gear.

The results of the R&D program to improve signal reliability and effectiveness have been discussed in Section 4. Solar powered lights, 6 year buoy paint systems, and extended life dayboards have been developed and are now in use. Plastic and synthetic foam buoys, most of which are unlighted, now account for about 15% of the total buoy inventory. Some Booz-Allen recommendations regarding alternative buoy hull shapes (e.g., catamaran hull) have not proven viable. The assumption that many steel buoys could be replaced by plastic with a reduction in lifting capability has not held up as discussed in Section 4.

7.2.3 Offshore Buoy Tender Studies

One of the first studies conducted following the Booz-Allen study addressed alternative ways to implement the reduction in the offshore buoy tender fleet (US Coast Guard, 1971). The plan decided on was the one recommended by the Office of Engineering which included both "major" and "austere" renovations. No decisions were reached on the ultimate replacement of the renovated vessels at the end of their useful service lives. Ultimately, 14 WLBs received a major renovation (15-20 year extension of life expectancy) between 1974 and 1979, and 12 received an austere renovation (7-10 year extension of life expectancy) between 1973 and 1976.

In the early 1980s, the Coast Guard embarked on a Service Life Extension Project (SLEP) for 14 WLBs (4 that had not been renovated and 8 that had undergone an austere renovation) that would extend their service lives for 15 years (US Coast Guard, 1982). Experience showed that there was little reduction in the maintenance cost following SLEP and the project was discontinued in 1992 after completing the SLEP on 9 vessels (US Coast Guard, 1994b). An excellent description of vessel condition studies and vessel replacement studies (with references) is contained in the Short Range Aids to Navigation Mission Analysis (US Coast Guard, 1994b).

7.2.4 River Tender Studies

For the river environment, Gathy and Danahy (1969) studied western river aids to navigation operations for FY68 to provide a baseline for comparing the existing system with any alternate system or system component. The report included operating costs, commercial usage, and other pertinent data for the rivers. Booz-Allen (1970c) recommended the extensive use of River ANTs (dependent on the development of

plastic buoys suitable for use in the open river environment--fast water buoys). River tenders would be used to service shore structures. Excess river tenders would be surplused and no replacement vessels would be needed until the 1990s. Because of the plastic buoy development problems, RANTs were not widely deployed and the major reduction in river tenders was not immediately realized. Based on a proposal from the Second District, a number of crews were combined in 1977 and the number of river tenders was reduced from 22 to 18. A Second District Quality Action Team recently (1992) developed a linear regression based River Resource Allocation Model that can be used for leveling workload among a given set of river tenders (US Coast Guard, 1994b).

7.2.5 Construction Tender Studies

The Booz-Allen study indicated that the then existing number of construction tenders (10) was adequate, although some modernization would be required. An internal study immediately followed completion of the Booz-Allen study. It defined the workload expected for inland construction tenders in the 1980 time frame and identified new resources required to replace obsolete tenders and provide the additional capability required due to the buoys to beacons program. It identified a construction requirement for ten additional WLICs. The construction program was approved for eight WLICs developed along the lines of a Specific Operational Requirement (SOR) prepared by the Eight District. The original plan was based on a pusher-barge combination, but changes in expected operational deployment led to a single unit 160' design (US Coast Guard, 1972). Escalating construction costs for the 160' WLIC coupled with lower than expected utilization as reflected in operating statistics led to a reevaluation of the program (US Coast Guard, 1976). This study identified a need for six of the original eight construction tenders approved in 1972. Using additional information about the material condition of some of the vessels to be replaced, it was decided to halt the new construction program at four 160' WLICs and to "improve" two 100' WLIs that use construction barges.

7.3 1983 SRA and Related Studies

7.3.1 1983 SRA Study

In response to an OMB request for an analysis consistent with Circular A-76, the Coast Guard conducted a comprehensive review of the Short Range Aids to Navigation (SRA) program and of the ships, facilities, and personnel assigned to accomplish the mission (US Coast Guard, 1983). The study addressed SRA elements in four segments: offshore, coastal and inland, Great Lakes, and river. In each section, the study addressed servicing requirements, tender utilization and cost, system planning factors, long term system alternatives, cost analysis of operational alternatives, and a summary and recommendations. The study concluded that the Coast Guard should continue to operate and staff all buoy tenders and ANTs with military crews. The study concluded that the total number of aids deployed is adequate for present safety of navigation requirements, and that there were no developments in the foreseeable future that would permit a reduction of the aids employed or reduce the size and weight of present equipment. The present number and deployment of tenders are generally necessary to meet the existing discrepancy response criteria, and that the Coast Guard should consider faster tenders when planning for replacement vessels. For the Great Lakes, use of tug/barge combinations could result in a reduction of buoy tenders.

The study included a substantive cost analysis that constructed costs for various alternatives using personnel costs (using Coast Guard standard costs), direct operating costs (fuel and maintenance), and capital costs (depreciation). For commercial alternatives, profit and overhead are also included. These constructed costs are used to evaluate the alternatives. The result is that Coast Guard owned and operated is the alternative of choice in all operating segments.

In obtaining the actual operating and personnel costs of $214 million attributed to SRA operations in FY81, $117 million were direct operating costs and $96 million were support costs. It is not clear from the report, but it is likely that operating units, such as Bases, are included in the support costs. It is also likely that 100% of the Base cost was assigned to SRA, regardless of the unit's actual use (e.g., high SAR activity). The report notes that the cost model is not directly relatable to alternative servicing options, and as an example, states that not all of the costs allocated to the offshore segment will be affected by changes in the mode of servicing offshore aids to navigation. Therefore, each alternative servicing option must include an analysis of those costs that are affected by the option under consideration. Change 1 to the report adds that for this reason, this cost allocation model was not used further in the study. This observation justifies the use of the constructed cost models described above.

SRAMA (US Coast Guard, 1994b) included a thorough review and evaluation of the SRA Study. It noted that in attempting to identify resource requirements, the SRA Study focused solely on discrepancy response (then requiring *correction* within 48 hours of notification for routine discrepancies and later changed to *response* within a specified time, depending on the severity of the discrepancy) as a driver of fleet size. The study also concluded that with this discrepancy policy, faster vessels would be of most benefit on the East coast where larger response circles might eliminate the need for one or more ships. A later study (Brown et al., 1992) concluded that speed would contribute most in the Pacific, and not where the highest concentration of buoys occurred. The SRA Study concluded that electronic navigation would not substantially affect the need for traditional visual aids, but SRAMA noted that the advent of DGPS and Electronic Chart Display and Information Systems (ECDIS) will likely reduce the need for visual aids.

In the coastal and inland segment, SRAMA supported the SRA conclusions except for faster vessels for discrepancy response. Speed requirements should be based on increasing productivity. On the Great Lakes, the SRA Study concluded that only one WLB was required on the Great Lakes (Lake Superior) for seakeeping reasons. Later studies recommend two vessels with WLB seakeeping capabilities. The SRA Study included a good description of river operations. Since the SRA Study that recommended replacement of 10 WLR barges, 11 130' river barges were constructed between 1985 and 1989. The SRA Study recommended faster replacement WLRs, but SRAMA suggests that due to draft and deck load requirements, such an upgrade is not likely to be economically feasible.

7.3.2 Follow On Studies

The 1983 SRA Study, despite its thoroughness and volume in describing the program, did not provide sufficient analysis to determine the appropriate service force mix in order to support the acquisition of replacement offshore and coastal buoy

tenders. One of the continuing issues in the replacement analysis involved the multi-mission use of the buoy tenders. Walker, Pritchett, Lincoln, and Stevens (1987) identified the capabilities provided by the 1987 fleet of 28 offshore buoy tenders and 12 coastal buoy tenders by summarizing the employment history over the past five years. Projections for future buoy tender usage were also presented. The coastal buoy tenders have spent nearly 87% of their time servicing aids to navigation over the previous five years. The balance of their time was spent supporting other missions such as search and rescue, law enforcement, training and other miscellaneous missions. Offshore buoy tenders have been used as multi-mission platforms, spending about 56% of their time servicing aids to navigation, 13% on search and rescue, 9% on law enforcement and 7% on training. The offshore tenders are also engaged to a lesser degree in military operations, icebreaking, and a variety of miscellaneous missions. The Aids to Navigation Division examined the same utilization question in addressing questions posed by OST regarding multi-mission use of WLBs (US Coast Guard, 1987c). The report documents WLB usage for FY82-FY86 (includes all Abstract of Operations hours) by district and also shows that the average SRA use was relatively constant over the past five years, averaging about 58% of all underway time. The report noted the excess time available is used in other missions. However, the paper emphasized that the replacement WLBs will be planned to only meet SRA requirements--no multi-mission use will be used to justify the number and location of WLBs. It is recognized that some excess capability may be available in certain areas depending on the SRA load. This single mission focus was later changed (Ihnat, 1992).

Several studies were conducted at the Volpe National Transportation Systems Center in the mid-1980s that addressed service force mix questions. The first studies developed a methodology and collected service time data in the First District (Blumensteil and Skaliotis, 1984; Skaliotis, 1984). These were followed by the development of a Service Force Mix (SFM) simulation model in Pascal for the Coast Guard Standard Workstation that applied the methodology previously developed (Skaliotis, 1987a, 1987b).

The 1983 SRA Study concluded, on the basis of a constructed cost analysis, that all aids to navigation operations should be conducted using Coast Guard equipment and military crews. However, contracting some activities had been part of normal operations (e.g., lamplighters, fixed aid construction, lighthouse repair). An experiment was conducted to evaluate the feasibility of contracting ATON servicing on selected waterways, performing the functions that would otherwise be performed by an ANT. Five low risk waterways were considered. All bids received exceeded the government estimate. Of the five areas, three contracts were awarded for operations over two and one-half years (FY87-FY89).

Thacker (1989) conducted an internal evaluation and concluded that performance ranged from unsatisfactory to excellent as follows: Merrimack River and Ipswich Bay--unsatisfactory; New Jersey ICW--unsatisfactory; Snake and Willamette Rivers--excellent. Discrepancy response, quality of work, and timely, accurate reports are the primary areas where contractors seem to have the most difficulty meeting contract requirements. Coast Guard contracting officers were located at MLCs, but COTR and QAE personnel were in district offices and local units. There appeared to be timeliness issues in administering the contracts and the report concluded that the CG ability to administer these contracts was marginal. Routine contract administration was

marked by long delays. The report concludes that there was no cost, technical, or administrative advantage in contracting out this ATON function to commercial activities.

Because this study was conducted internally, a final report was not prepared. Rather, a contracted study was conducted by the Volpe National Transportation Systems Center to evaluate the ATON contracting trial. This evaluation indicated that performance was satisfactory under all contracts (Tung, Skaliotis, Goeddel, Flahive, and Cook (1990). The selection of the areas to be evaluated was valid and the aids were representative of workload in the various districts. The statements of work were not clearly written which may have contributed to higher bids on a fixed price contract when the deliverable was uncertain. The contracts in the 1st and 13th districts were a combination of fixed and variable price components. The VNTSC evaluation of contract costs generally agreed with the Coast Guard's estimate. The VNTSC evaluation noted that the Coast Guard evaluation of the contractors' performance was unsatisfactory in two cases, but VNTSC noted that the contractor performance was comparable to that of other Coast Guard units in the program. The VNTSC evaluation concluded that there does not appear to be any cost or performance advantage for an expanded contracting effort for ANT. The report also indicated that there are no obvious candidates of floating resources that could be eliminated through privatization. Finally, the report noted that a decision to contract aids should not be based solely on cost. It must consider the impacts on the USCG organization and its ability to respond to myriad statutory and regulatory requirements.

7.4 SFM 2000, SRAMA, and Related Studies

7.4.1 SFM 2000

In order to assess the effects of alternative mixes of replacement offshore and coastal buoy tenders, the Coast Guard sponsored an effort at the VNTSC to analyze fleet requirements and provide the Coast Guard with a methodology for periodically validating those requirements. The resulting project is termed the Service Force Mix (SFM) 2000 study consisting of four volumes: an overview (Brown and Schwenk, 1992), description of the Decision Support System (DSS) (Brown, et al., 1992), aid assignment and vessel summary reports, (Brown, Schwenk, and Bucciarelli, 1992), and specification of multi-mission requirements (Ihnat, 1992).

The main volume of the study report documented current ATON operations, the concept, development, and operation of the DSS, the data utilized by the DSS, the validation of the DSS, and the proposed service force mix. The heart of the analysis is the DSS. Although a similar analysis was conducted by VNTSC in 1986-1987, the previous simulation model could not have taken advantage of the significant computer hardware and software advances in the five years that followed. The earlier model did not provide graphical displays and related geographical information system capabilities to aid data preparation and analysis of the results. It required manual data input, and was very limited in its ability to address "what-if" types of questions. The SFM 2000 study also considered using the "ANGEL" single vessel simulation model developed at the Coast Guard R&D Center (Kingsley, Klewsczewski, and Smith, 1990), but this also was judged to be lacking the geographic capabilities.

The study constructed the new DSS using a commercial Geographic Information System (GIS) software program named "TransCAD." This software has a strong built in

transportation analysis capability. The DSS is run for each operating area and scenario to find an efficient set of assignments of ATON to platforms and platforms to home ports. The DSS is run separately for each defined service area and used iteratively to seek an efficient set of assignments of ATON to platforms and platforms to home ports. The following steps are for all geographic areas to produce a specific fleet size and mix.

1. Input data are developed for ATON, vessels, home ports, travel times, and service times.
2. Vessels are assigned to home ports.
3. ATON are assigned to vessels.
4. Trip routes are developed and performed for each vessel using a modified traveling salesman algorithm. The DSS models the activities over a one year period.
5. Outputs are evaluated. Where necessary, inputs are adjusted to yield outputs that conform with operating guidelines.

The model estimates resource hours for discrepancy response by computing the expected number of discrepancies per aid (from ATONIS and the Buoy Tender Operations Survey, relying on the total survey responses as determinant), and multiplying by the number of aids assigned, and then multiplying by the average time spent servicing an assigned aid (includes service and travel time) that is an output from the DSS. There is no explicit modeling of discrepancies in the DSS model.

Service times were collected by Blumensteil, and Skaliotis (1984) for the First District. The SFM 2000 study determined that better estimates reflecting all environmental conditions were required and used a Buoy Tender Operations Survey to obtain service time estimates for individual vessels and types of aids. Because the service time estimates were obtained for existing servicing assignments, adjustments to service times were required if a WLMR was assigned to service an aid formerly serviced by a WLBR or vice versa. When a WLMR was assigned, the service time was the maximum of the WLBR and WLMR service times; when a WLBR was assigned, the service time was the minimum of the two service times. The study report identifies the types of service that are performed over a six year cycle, but does not indicate how these are distributed in a one year run of the model. The DSS uses a trip parameter of 72 hours underway on a single trip (10 days for Caribbean, Alaska, Hawaii, and Great Lakes), and uses a 10 hour workday for WLMRs and a 12 hour workday for WLBRs. An adjustment in resource hours used is made when simultaneous servicing is carried out by small boat. Weather penalties are estimated as additional resource hours. Delays are not explicitly included in the model.

Volume III of the study developed the multi-mission requirements that specified a minimum WLBR fleet of 16 vessels (Ihnat, 1992), and was supported by an internal review (US Coast Guard, 1992). The study considered buoy tender employment categories, historical tender employment data, the determination of underway hours per underway day, and projected impacts on multi-mission requirements resulting from alternative replacement fleet scenarios. The WLBRs are expected to be "multi-mission," meaning that they will average about 60% of their employment in the ATON mission; WLMRs will be "focused mission" meaning 85% ATON employment. This assumes that a WLBR is available for ATON for 90 operational days (based on 60% of a planned 150 operational days per year). Because WLBs have traditionally been underway for 14 hours per day, the target resource hours for WLBRs were set at 1260 hours. For WLMRs, 85% ATON in 150 operational days at an average of 10 hours per day

underway, the target resource hours were set at 1275 hours. WLBR speeds were 12 knots on the East and Gulf Coasts and the Great Lakes, and 13 knots in the Pacific; WLMR speed was 10 knots.

The DSS first considers ATON that require a WLBR, and second, those that are serviceable by WLBRs. If the available WLBRs are fully utilized and additional ATON require WLBRs, adjacent areas are considered or additional WLBRs are assigned. This is repeated for all areas and the result is a specification of the number of WLBRs that are required. If the WLBRs are not fully utilized, other aids are assigned to meet the target resource hours (1260). The process is repeated for WLMRs considering aids that are not serviceable by buoy boats (BUSLRs). The procedure is repeated until employment reaches the target resource hours (1275). If ATON requiring WLMRs remain, WLMRs are added if time is not available in an adjacent area. Any remaining ATON are serviceable by BUSLRs.

The study recommended a mix of 16 WLBRs (minimum for multi-mission) and 14 WLMRs. An incremental analysis showed that as the number of WLBRs increased from 16 to 19, the number of WLMRs decreased from 14 to 11--the total fleet size remained constant at 30. In a later paper, Bucciarelli and Brown (1995) reported that decreases in the WLBR requirement resulted in a constant fleet size until there were 12 WLBRs--then the required WLMRs were 19, a fleet size of 31. They concluded that the ATON work requires 30 vessels, and the mix is determined by the multi-mission requirements of the WLBRs.

The study included a number of sensitivity tests. A 20% increase in all vessel speeds would result in a decrease by only one vessel. However, a 20% decrease in speed would result in an increase of five vessels (three of the five would be in districts with long distances--Districts 7, 14, and 17). A 25% reduction in service times results in a decrease of one vessel, and a 25% increase in service times would require an increase of one vessel. A 50% change in the weather impact would result in a one vessel change in the Atlantic/Gulf region. A 20% increase in the target resource hours to 1500 hours per year results in a decrease of eight vessels, while a 20% decrease to 1000 hours results in a five vessel increase. Overall, the results are most sensitive to the assumption regarding ATON resource hours.

7.4.2 BUSL and Construction Tender Studies

The DSS developed for SFM 2000 was originally used to fully load the WLBR and WLMR resources. The remaining ATON are potential candidates for BUSL assignment. The Coast Guard had embarked on a program to replace small buoy boats with a single class of 49' stern loading buoy boats (BUSL). Brown (1993) extended the analysis provided in the SFM 2000 project to include all of the Coast Guard's smaller buoy handling resources. The DSS developed for SFM 2000 was used to evaluate current and replacement buoy boats. The analysis was restricted to buoy servicing operations. Fixed aids to navigation were considered too diverse to model well since they can be serviced by vehicle, small boat, or other means. In addition, the DSS operates by fully loading available resources. The study concluded that 27 49' BUSLs were required to replace existing boats and to replace WLB/WLM capability reduced by the fleet mix selected in the SFM 2000 study. It also concluded that seven additional BUSLs could assume nearly all of the buoy servicing responsibilities of the two 100' and four 65' WLIs, and that up to ten BUSLs could be effectively employed to assume

responsibility for buoys currently assigned to WLICs. The report did not make any specific recommendations regarding inland and inland construction tenders. The report was distributed to District Commanders and their review and analyses are included in Appendix E to SRAMA.

Brown, Bucciarelli, and Leo (1994) analyzed inland construction tender requirements in conjunction with SRAMA. Three areas were examined: a determination of the optimum number of WLICs needed for the construction component of current WLIC work; a comparison of Coast Guard construction tender costs with representative private sector costs; and an assessment of the mission related factors concerning WLICs that need to be considered before reducing the construction tender fleet or contracting for the construction of fixed aids to navigation.

The analysis concluded that 11 WLICs are required for construction purposes (the current fleet is 16); private sector costs exceed those of Coast Guard construction tenders fully employed on construction activities; and mission-related factors – including having the capability of shifting tenders in response to peaks in construction activity and vessel maintenance requirements – need to be included in any decision to alter the size and location of the construction tender fleet. The restriction of WLICs to construction work requires that seven BUSLs be provided for WLIC buoy work. The analysis was supported by use of the Service Force Mix DSS that had previously been used to determine the WLB/WLM requirements and the BUSL requirements. The study also identifies the need for a much more complete database that captures service performance. This is a critical issue for any efforts to measure system and resource performance.

7.4.3 Short Range Aids to Navigation Mission Analysis (SRAMA)

The Short Range Aids to Navigation Mission Analysis (SRAMA) was conducted by the Short Range Aids to Navigation Division to validate previous studies and integrate mission definition and capabilities of all SRA resources into a single document (US Coast Guard, 1994b). SRAMA included a general description of the SRA program and a comprehensive review and analysis of the major ATON analyses that had been conducted since 1970. Based on that review, several additional analyses, in-house data analysis, and field input, SRAMA provided recommendations for a course of action for the program for the following 5-15 year period. The primary sources included the SFM 2000 study (Brown, et al., 1992), the BUSL study (Brown, 1993), the WLIC study (Brown, Bucciarelli, and Leo, 1994), and a Second District Quality Action Team report on River Tenders that created a River Resource Allocation Model for balancing tender workload. Like the Booz-Allen study, SRAMA examined the aids to navigation *system* and the recommendations represent an integrated whole.

The primary recommendation comprises a fleet restructuring plan. The plan calls for a fleet mix of 16 WLBRs and 14 WLMRs, decommission all WLIs and assign responsibilities to BUSLs, convert BUCKTHORN to a construction tender and decommission the three oldest WLICs, reassign one 55' ANB to Alaska to replace the WLI, convert on 75' WLIC to a WLR, and supplement the reduced fleet with new 49' BUSLs (a total of 36 are now required). The expected savings are $3.8 million per year. The report requires only insignificant changes in the SRA system to achieve the savings. The SRAMA report includes the District evaluations of the BUSL

recommendations and a number of unresolved issues need to be addressed that will likely affect the service force mix described above.

SRAMA emphasized that the fleet mix should be validated in five years. In addition, SRAMA noted that replacement of the ANB will likely be required in the next 5-15 years. The specifications for the ANB were developed following the Booz-Allen study and designed to meet the needs of the perceived changing ATON world. It is important that the boat needs for ANTs be properly evaluated to determine the right specifications for the replacement ANB. An as yet undefined requirement is the need for a "surge" capacity in order to be able to respond to short term changes in demand. SFM 2000 acknowledge the requirement and accommodated it by requiring that the vessels were employed between 80% and 100% of the target resource hours.

SRAMA identified the need for an effort to monitor trends in ATON technology and customer needs to develop leading indicators that will assist in determining future program direction. SRAMA particularly noted increased servicing intervals and improved electronic navigation. An additional need is identified that requires the development of a quantitative and defensible methodology for making future repair/replace decisions for resources.

The SRAMA report included a thorough evaluation of previous ATON studies. The evaluation in the present report has benefited greatly from the insights provided in SRAMA.

7.5 Servicing Policy and Discrepancy Response Studies

Aid servicing and discrepancy response policies have evolved as signal hardware reliability has improved and other advances in buoy technology have been realized. Prior to 1973, servicing requirements included quarterly inspections, annual mooring inspections, and buoy reliefs on a four year cycle. Recharge times for lighted aids were driven by the rate at which the primary batteries were depleted, ranging from one to three years. The Booz-Allen (1970c) study recommended extending the servicing intervals. The recommended service force mix used the extended intervals as a basis for planning. In 1973, the servicing intervals were changed significantly. Inspections for lights and buoys were extended to one year, and inspections for daybeacons were extended to every two years. Intervals between mooring inspections were extended to two years, and reliefs were extended to six years. Recharges were unchanged.

Before 1972, Coast Guard policy was to respond to all discrepancies within two hours of notification. When the Aids to Navigation Administration Manual was published in 1972, the policy changed to specify the maximum allowable time to *correct* the discrepancy and categorized the nature of the response: Immediate--correct as soon as possible (all manned aids and LNBs); Priority--correct within 24 hours; Routine--correct within 48 hours; and Deferred--correct during next routine visit. Guidance was provided to assist in the subjective determination of the response category. Despite guidance that buoy tenders were not to be placed in a standby status to ensure that this policy was met, some districts did so. In 1979, Commandant (ALDIST 311/79) abolished the specific levels of discrepancy response and left all decisions regarding discrepancy response to the District Commander. This local policy remained in effect until 1982 when a Discrepancy Response Decision Guide was promulgated in a change to the

Administration Manual. This policy changed the time from completion of corrective action to the time that the unit *responds* to the discrepancy. Five levels of discrepancy response were defined: Immediate--respond immediately; High Priority--respond within 18 hours; Priority--respond within 36 hours; Routine--respond within 72 hours; and Decision/Deferred--respond when servicing plans allow.

The 1983 SRA Study (US Coast Guard, 1983) reviewed the servicing and discrepancy response policies, and compared USCG policies with those of other nations. The conclusion was that the present policies were less conservative than any others. The study also noted the lack of detailed discrepancy data available to be able to evaluate discrepancy response performance. The study did use Third District discrepancy data from a local information system to estimate an average response time between 52 and 70 hours (less for Category I buoy). These data reflected performance from the period prior to the new policy.

In 1987, the Aids to Navigation Division addressed questions posed by the Office of the Secretary of Transportation regarding routine servicing of aids to navigation and ATON discrepancy response policy. The paper reviewed the changes in both the servicing policy and discrepancy response policy over the previous 20 years. The US policies are compared with other nations and it is noted that the US policies are more relaxed than any other country. The study evaluated extending some servicing intervals to 18 or 24 months. The lamps and guano on solar panels and daymarks were reported as limiting factors on increasing servicing intervals. Environmental factors also affect when aids can be serviced. The paper noted that extending an annual service to 18 months may schedule it when weather is unfavorable. The existing annual schedule means that senior personnel on ships will visit an aid twice during a normal tour--the first visit is with more experienced personnel and the second visit as the senior person. Extending the service interval may mean that there will be no person experienced with a particular aid when it is serviced. The report concluded that the present servicing policy can not be extended beyond a year without increasing discrepancy rates or seriously degrading daymark signal quality. The paper also reviewed discrepancy response policy. The study concluded that under the 1982 policy, buoy tender numbers and homeports are not seriously affected by discrepancy response policies. It is the workload that is the key factor, of which discrepancy response is only a minor part. The paper reported the use of the Service Force Mix (SFM) model (Skaliotis, 1987a) to evaluate changes in the discrepancy response policy. The example showed a 20% reduction (from 754 hours to 603 hours) for a WLB to service all assigned aids in going from the current response policy to a deferred response for all discrepancies. Discrepancy rates and other details are not provided. The ATON utilization appears to be very low in this case. The report also included correction time data for aids in a 5 district sample (1st, 5th, 11th, 12th, and 13th) for the first quarter of 1987. Of the 761 discrepancies, 445 were "Deferred." A total of 56 were corrected by a WLB or WLM. Of these, one was Immediate (75 hours), 13 were Priority (36 hours), and 42 were Routine (27 hours) (mean completion times shown in parentheses). The response times are not included in the data base. Given all of the considerations raised, the paper concluded that the resource need is fairly insensitive to relaxing these policies.

Another review of servicing policy was conducted by Fremont-Smith (1994). The report reviewed the history of changes to servicing policies, and included the numerous comments regarding discrepancy response, WAMS, and servicing policy collected and reported by Murphy (1993), as well as a letter and comments from the Canadian Coast

Guard indicating that it is studying the possibility of relaxing the discrepancy response and servicing policy for Canadian ATON. Based on a review of all of the comments, the study recommended that there is "little need any longer to routinely service USCG minor lights, buoys and daymarkers on a rigid, annual basis". The report recommended a maximum servicing interval for ocean buoys, minor lights and daybeacons of two years and a maximum mooring inspection interval of six years. The recommended change to the Aids to Navigation Manual specifies maximum biennial inspection of buoys and fixed structures. Two years is specified as the normal period between mooring inspections in the proposed change to the Administration Manual, but it may be modified (extended or shortened) depending on location and wear. Scheduled recharges (replacements) should be determined on the rated battery discharge time and scheduled to coincide with scheduled visits to the aid. Also included is an ATON Servicing Interval Flowchart (SIF) that is intended to assist units in determining appropriate servicing frequencies. Annual evaluation visits are required for each waterway to conduct an overall assessment of all aids in the waterway. It is interesting to realize that this recommendation was based only on interviews and qualitative factors. There was no analysis of discrepancy or maintenance data, and no evaluation of the effects on servicing resources.

7.6 Analytic Models Supporting Service Force Mix Studies

Several other models have been developed that may have applicability to aids to navigation planning in the future. One such model is the ATON General Event-Step Logistics model (ANGEL) that was developed at the Coast Guard R&D Center (Kingsley, Klesczewski, and Smith, 1988, 1990). This model is a discrete event simulation model written in SIMSCRIPT II.5 for evaluating given buoy tender designs operating in selected geographical regions. The model included the following tender activities: working of a buoy (model relies on visual positioning of aids), docking to resupply the tender, R&R for the crew, anchoring due to bad weather, waiting for the desired time in which to work a buoy, and the transiting of the tender between a set of buoys. ANGEL incorporated a Route Planning Model (RPM) to schedule the buoys that the tender is to service (Cline and King, 1987, 1988; Cline, King, and Meyering, 1992). The environmental factors are incorporated using probability distributions of various types. The model results are shown for two examples: Long Island Sound, and the 13th District. The model results demonstrate the relative performance of alternative buoy tender designs using the sponsor's performance requirements as evaluation criteria. A final report for this project was never published. Subsequent discussion with one of the authors (Kingsley) suggests that if ANGEL is to be used, it should be recoded in a language supporting animation.

Brown, Dell, and Farmer (1996) described an optimization model developed to schedule Coast Guard District cutters to quarterly patrols and standby status for search and rescue, law enforcement, and pollution control. The model was implemented for the First Coast Guard district involving 16 cutters. Each cutter is assigned weekly to one of six statuses to ensure patrol coverage, enforce equitable distribution of patrols, and honor restrictions on consecutive cutter statuses. The problem is modeled as an elastic mixed-integer program that yielded face-valid schedules that were superior to the manually prepared ones. Similar scheduling problems may exist to ATON units when considering the planning of servicing trips using routings developed through a Cline and King (1992) model or a SFM DSS model (Brown, et al., 1992).

7.7 Service Force Mix References

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8.0 SUMMARY OF STUDIES FOCUSING ON ADVANCED TECHNOLOGIES

The Coast Guard has been involved in developing and implementing advanced technologies for navigation. As noted in Section 3.2, the Coast Guard was involved in developing the first National Plan for Navigation in the late 1960s. The primary focus of that effort was to integrate the various responsibilities for LORAN-A, LORAN-C, and OMEGA. That plan involving primarily electronic technologies has continued over the years. The most recent version is the *1996 Federal Radionavigation Plan* (US Department of Transportation, 1997). The Federal Radionavigation Plan (FRP) delineates policies and plans for radionavigation services provided by the US Government to ensure efficient use of resources and full protection of national interests. Developed jointly by the US Departments of Defense and Transportation, the FRP sets forth the Federal interagency approach to the implementation and operation of radionavigation systems.

Radionavigation systems accuracy and reliability have developed to the point where advanced technologies using radionavigation are viable alternatives for harbor and harbor-entrance navigation. Polant (1993) proposed packaging "Global Dial Tone," Differential GPS, Electronic Charts, and Automated Dependent Surveillance as the required "Coast Guard five-mile-an-hour-bumper." He predicted that the Coast Guard will become the operator of the ground portion of GPS, and further predicted that the average boater will use GPS and electronic charts. Ecker (1995) identified the emerging technologies that may play a significant role in waterways management in the future, including:

- Satellite-based navigation--GPS
- Microcomputers
- Geomatics--science and technology of spatial information management
- New lighting source for navigational ranges, buoys, and fixed navigation aids

Improved systems include:

- GPS/DGPS
- ECDIS
- Improved marine radar
- New buoy system
- New minor light
- Automated vessel tracking

New program initiatives include:

- DGPS broadcast services
- ECDIS updating
- Waterways management assessment that includes:
  waterways design and ATON mix/selection,
  navigation risk assessment,
  waterways project cost/benefit analysis, and
  ATON resource allocation.

Advanced technologies for aids (e.g., buoyant beacons, new light sources) were discussed in Section 4.5. This section focuses on electronic technologies including display studies, ECDIS studies, and DGPS studies that are used in the harbor and harbor-entrance environment.

8.1 Electronic Aid and Display Evaluation Studies

The earliest advanced technology study involved a follow-the-wire system that used an energized cable laid on a channel bottom precisely on the desired trackline, and sensing coils and display equipment mounted on the ship to determine and indicate the direction of the cable from the ship (McIntosh, 1972). This experiment was conducted in the Muskegon channel connecting Lake Michigan and Lake Muskegon using CGC WOODBINE. The five mile long cable was energized by a 400 Hz motor generator set. The circuit was completed using a ground return. The system proved to be reliable, accurate, repeatable, inexpensive and easy to use.

Schryver (1983) used the CAORF ship simulator to examine collision avoidance problem solving using variable modes of presentation on an Automatic Radar Plotting Aid (ARPA). One group of licensed masters and mates with watchstanding experience was aided with relative motion vectors attached to target echoes in an unstabilized, "heading up," relative motion PPI display. A second group was similarly aided with true motion vectors. During experimental trials, test subjects entered the simulated bridge to observe a developing traffic situation and assume the conn. The situation was assessed by the subject until an irreversible course of action was initiated. Subjects using true vector displays were significantly more likely to take evasive action as compared to those using relative vector displays, but the effect was confined to mates.

A series of three simulator-based experiments in the early 1980s provided significant insight into the use of electronic displays. Cooper and Marino (1980) conducted a miniexperiment, a predecessor to more lengthy experimentation, using an abbreviated scenario involving a 30 degree bend in a channel to operationally simulate 18 display formats. Six digital, ten graphic, and two perspective displays were evaluated. The digital display was designed to provide trackkeeping and turning information that would enable pilot to transit the waterway while using an inexpensive digital (alphanumeric or numeric only) display. The graphic display was designed to provide a pictorial representation of ownship in the waterway similar to the way it is viewed on radar, contemporary collision avoidance, or navigation option displays. The perspective display was designed to portray the perspective scene as viewed out of the forward bridge windows. Overall, the results suggested that the graphic display is the best.

Cooper, Marino, and Bertsche (1981a) used a ship's bridge simulation of electronic radio aids to navigation displays to compare digital, graphic, perspective, and steering display formats for five displays recommended from the miniexperiment along with two new steering displays. The main finding was that a true motion trackup graphic display with either course or heading vectors is recommended as a benchmark for future experimentation. The experiment was conducted using perfect position information.

In the follow up experiment that considered ownship position error, Cooper, Marino, and Bertsche (1981b) used a "benchmark" true motion, trackup graphic display recommended in the RA-1 experiment to conduct simulated poor visibility runs of a 30,000 dwt tanker around a 35-degree left bend in a 500 foot wide channel. The display used a heading vector and a scaled image of ownship. The simulation with noise and the characteristics of an actual navigation system uncovered a previously unaddressed problem: the effects on pilotage of display lag and jitter. Jitter or "jumping around" results from random position errors in the navigation system. Mathematical tracker

filters smooth out the jitter, but cause a display lag. Jitter and display lag are inversely related. Consequently, the pilot never knows the real position of the ship. The main effect is that the displayed image reacts differently to maneuvering actions than does the real ship and actual performance is degraded. In this experiment, the use of electronic radio aids to navigation display alone never achieved trackkeeping or maneuvering performance comparable to those simulations where pilots could view out the windows.

Cooper and Bertsche (1981) conducted an at-sea evaluation to determine the effectiveness of various fixed, floating, and electronic aids to navigation on harbor pilotage. Four different pilotage techniques were used: visual ranges, traditional radar piloting, radar course piloting using a RACON, and piloting using the Sperry CAS II PATH display. The experiment used pilot's accuracy of judging their position within the channel as a primary measure for comparing the effectiveness of the piloting techniques. Actual ship position was measured using a LORAN-C tracking system developed by the Coast Guard R&D Center. Results indicated that visual pilotage produced the best performance and that traditional radar pilotage was substantially poorer. Use of the PATH display for pilotage proved only as effective as radar, but there were indications that additional experience by the pilots would have substantially improved their performance.

An evaluation of more complex display devices was conducted by Gynther and Smith (1989) (see also Mandler and Smith, 1990; and Mandler, Smith, and Gynther, 1990, 1991). This study evaluated the use of electronic navigation systems for piloting deep-draft vessels in restricted waterways using the ships bridge simulator at the USCG Academy. The purpose of the experiment was to evaluate accuracy requirements for electronic navigation systems for use in periods of low visibility, and to examine the trade-offs among accuracy, visibility, and the sophistication of the device. Three display devices were used simulating existing or soon to be available devices. One device (A) displayed the waterway in a track-up display. Speed, both along track and crosstrack, was provided digitally. Another device (B) was similar with a north-up display, and a third display (C) only provided digital information. The scenario involved navigating a 500-foot wide channel with a 35° left turn. All of the electronic devices resulted in better performance than visual piloting in the recovery and trackkeeping sections. Devices A and B resulted in better turn performance than visual piloting in low visibility. The digital only device (C) was inadequate for turns in low visibility. Pilot performance in the 8-20 meter 2drms range of accuracy approximated visual piloting performance. The findings suggest that navigation in restricted waterways is possible in reduced visibility with the present technology of electronic navigational aids.

An Integrated Navigational System (INS) display was examined in a 1990-91 experiment (Smith and Mandler, 1992). A radar overlay and a rate of turn indicator were included in a display designed to be consistent with IMO Provisional Performance Standards for ECDIS. The experiments showed that increased display complexity and positioning accuracy had positive effects, especially in the more difficult turn maneuver and in severely-reduced visibility.

Gonin and Crowell (1997) reported on the results of the CG R&D Center's evaluation of several commercial Electronic Chart Systems (ECS) for use aboard Coast Guard cutters. A secondary purpose of the report was to provide insight into the RTCM Recommended Standard for ECS that may assist individuals in the procurement,

development, regulation, and policy setting for ECS. The R&D program was initiated to examine the proposed RTCM standards for Electronic Chart Display and Information Systems (ECDIS). The results of the research have led to revision of the ECDIS standards and the development of standards for ECS. The current research included an operational valuation of three commercially available ECS for use on Coast Guard vessels. The highest level system included radar integrated with the ECS. The report includes an evaluation of each system installation. Based on that evaluation, the report includes guidance for choosing an ECS. The guidance addresses the functionality described in the RTCM standard and provides additional guidance based on the experience from the evaluations. The report recommends that the Coast Guard partner with ECS manufacturers and pursue a COTS acquisition policy rather than developing its own system. The operational evaluation was conducted in 1994. The report includes additional information on more recent systems (1997) and discusses future issues (raster chart data vs. vector data).

8.2 Electronic Chart Display and Information System (ECDIS) Studies

Electronic Chart Systems (ECS) provided a good means of assisting the process of navigation, but did not possess sufficient accuracy to serve as the basis for navigation in conjunction with position information from DGPS. Several Coast Guard studies examined various aspects of electronic charts and helped to form the standards for Electronic Chart Display and Information Systems (ECDIS). The international standards ensure that the information is of sufficient quality to assist safe navigation.

A necessary component in an ECDIS is an electronic navigational chart. MacRae, Stephenson, Leadholm, and Gonin (1992) examined the activities associated with transforming DX90 data structures to an intermediary Electronic Navigational Chart (ENC) format, developing the software to transform this intermediary ENC to a form which could be displayed as a System Electronic Navigational Chart (SENC), and developing display software to allow an operator to interact with the data. The overall conclusion was that the DX90 standard will support Electronic Chart Display and Information Systems (ECDIS) applications, but particular attention must be paid to the various conversions that have to take place.

Two ECDIS systems using a real-time simulation with the simulator at MSI/CAORF were evaluated by Smith, Akerstrom-Hoffman, Pizzariello, Siegel, Schreiber, and Gonin (1995) (see also Akerstrom-Hoffman, Pizzariello, Smith, Siegel, Schreiber, and Gonin, 1993; Akerstrom-Hoffman and Smith, 1993; Gonin, Smith, Akerstrom-Hoffman, Siegel, and Pizzariello, 1993; Gonin, Smith, Dowd, Akerstrom-Hoffman, Siegel, Pizzariello, and Schreiber, 1993; and Smith, Akerstrom-Hoffman, Pizzariello, Siegel, and Gonin, 1994). The scenarios involved transits through the coastal and harbor/harbor approach phases of navigation in New York or San Francisco with above normal workload. The single master/mate was responsible for all navigation, shiphandling, and collision avoidance activities. A single helmsman was provided. The scenarios were designed to have comparable levels of density of events. The two ECDIS systems included Offshore Systems Limited's Precision Integrated Navigation System and Robertson Marine Systems Incorporated's Disc Navigation System. Baseline conditions included plotting on a paper chart, radar/automated radar plotting aid (ARPA), and visual piloting. The ECDIS systems were added either with or without automatic updating of own ship's position, and with or without integrating radar features. ECDIS increased safety, both by decreasing the cross-track distance of own ship from

the planned route and by increasing the proportion of time that the mariner spent on look out and on collision avoidance. ECDIS significantly decreased the mariner workload for navigation when automatic updating of position was available. The mariners expressed a preference for a relatively simple chart display for route monitoring, with the immediate availability of a large set of chart information. No measurable effects of radar features on ECDIS were found, although mariners believed that this would be a valuable addition. When no ECDIS was available, visual piloting was the primary method for 73% of the 40 segments. ECDIS was the primary method of navigation for 67% of the 79 segments when automatic positioning was available. With ECDIS and no automatic position updating, radar/ARPA was the primary method in 61% of the 18 segments.

Gonin and Dowd (1995) conducted an at-sea verification of the simulator results. The evaluations took place on board USCGC BITTERSWEET and T/V KINGS POINTER. The experiment included both coastal and harbor/harbor approach navigation under good and poor visibility using a traditional bridge, ECDIS with radar, and ECDIS without radar. The study found that ECDIS with automatic positioning decreased the mean cross-track distance to approximately one third of what it was with conventional methods. In case of failure of the automatic positioning, necessitating manual positioning of ECDIS, cross-track distance is increased. EDCIS with automatic positioning decreased both the mean workload for navigation and the mean reported proportion of time spent on navigation. This is viewed as an increase in safety due to the availability of more time spent on lookout and collision avoidance. In the 1992 simulator experiment, there was no difference between ECDIS with radar and ECDIS without radar. In the at-sea evaluation, a better radar was used and mariners expressed a preference for an integrated ECDIS/RADAR/ARPA device with full capabilities for navigation and collision avoidance. Summaries of the 1991 and 1993 sea trials and the 1992 simulator experiment are included in Gonin, Dowd, and Alexander (1996).

Spalding and Alexander (1997) considered issues regarding the integration of ice navigation systems and ECDIS for navigation in ice infested waters. The structure of the system included a separate ECDIS that passed waypoint information to and from a separate Ice Navigation and Support System (INSS). The researchers concluded that developing a stand alone integrated system was beyond the scope of the resources available for the project and was going to be technically very difficult. The exchange of waypoint information using a standard National Marine Electronic Association (NEMA) interface for routes and waypoints and IHO S-57 data objects for ice information processed by the INSS would assure interchangability between manufacturers for either ECDIS or INSS components. The study concluded that the Coast Guard should use separate ECDIS and INSS components rather than develop and maintain an integrated system.

8.3 Differential Global Positioning System (DGPS) Studies

The Coast Guard has had an important role in the development of Differential Global Positioning Systems (DGPS). Pietraszewski, Spalding, Viehweg, and Luft (1988) reported on the Coast Guard research program to investigate C/A-code GPS and methods to improve its accuracy and integrity. The paper reported on the results of an evaluation of a differential GPS system. The proposed system was tested on both static and dynamic modes. Analysis of the stated DGPS test results demonstrated that the performance was within the 8m to 20m target established at the start of the project.

During the best conditions, the results were better than 8m (2 drms). The dynamic position involved a 42' Coast Guard patrol boat operating at 10 knots and 20 knots. A microwave ranging system was used to monitor the boat position. Again, the performance was within the 8m to 20m target. The various maneuvers demonstrated that carrier-aided DGPS is accurate enough to expose errors in the instrumentation or truth measurement. The reports notes several difficulties: no standard algorithm exists for "earth rotation correction." The issue of parametric synchronization should be reviewed by the RTCM SC-104. Because carrier-aiding is important in this application, the proposed RTCM SC-104 messages need to be reviewed to ensure that the necessary solutions for correcting carrier-aids navigation have been included.

Spalding, Krammes, and Pietraszewski (1991) tested a prototype differential GPS system using the Montauk Point, NY radiobeacon. Considering the general performance observed over the first six months of operation, and a detailed analysis of a one month period, the evaluation reported that the system met the accuracy goal of 10 meters 95% of the time, when the HDOP is less than 2.3. The prototype demonstrated that marine radiobeacons are a viable method of providing a public broadcast service and provide a signal comparable to various microwave systems used by the Coast Guard. The report strongly recommended DGPS as the preferred method for providing highly accurate positioning information. The 1996 Federal Radionavigation Plan implements this recommendation.

In 1993, Alexander and Spalding reviewed the technology used in currently available (1993) marine navigation and positioning systems. The focus was on those systems and components needed for ECDIS and Integrated Navigation Systems (INS). Specific technologies include GPS/DGPS, electronic charts (both IMO-compliant ECDIS, and electronic Chart systems--ECS), and automated radar positioning (circular polarization systems). The paper identified improvements needed in GPS receivers, GPS/ECDIS interface, high accuracy (GPS-qualified) charts, and primary and secondary positioning sensors and also discussed open architecture requirements

LaMance, Spalding, and Brown (1995) described an autonomous DGPS Fault Detection and Isolation (FDI) algorithm that can be implemented in the user's DGPS receiver. The algorithm is embedded in the NAVSAFE software developed by NAVSYS Corporation. The algorithm makes use of redundant measurements to test the validity of the DGPS solution. Earlier versions of the algorithm were unable to determine whether there was a failure in the algorithm or if the solution was valid in certain circumstances. To augment the RAIM process for this application, additional information is provided to the RAIM software to permit altitude aiding. In particular, a tide model was added. The modified models were tested in 1994-95 and the results clearly indicated that the altitude aiding provides the additional information needed to reduce the false alarms and warnings. With the improvements of the altitude aiding and high accuracy differential corrections, false alarms and warnings have been virtually eliminated.

The above research has focused on providing DGPS signals. Lunday, Spalding, and Dowd (1995) verified USCG DGPS broadcast parameters by testing several state-of-the-art Differential Global Positioning System (DGPS) Minimum-Shift-Keyed (MSK) receivers under varying conditions. The purpose of the effort was to determine the capability of commercially available receivers with respect to proposed USCG DGPS broadcast parameters and to test theorized optimal broadcast parameters (message

type and speed) with regard to static noise and carriers/jammer interference. The data showed that all of the tested units can receive MSK signals under the proposed USCG broadcast parameters. In the presence of atmospheric noise, message type 9-3 had an advantage over message type 1, agreeing with previous results. However, all receivers demonstrated vulnerability with respect to interference from other CW signals. Very strong jammers had an effect on the MSK signal reception, even when the jammer frequency was several kHz away from the MSK frequency. This latter observation needs further research.

Creamer, Cho, Morris, and Pisano (1997) conducted a mission needs analysis to identify the DGPS service requirements for meeting harbor entry and approach mission needs. The requirements analysis focuses on DGPS providing navigation information in low/zero visibility conditions equivalent to current levels of operation/casualties when used in conjunction with a baseline suite of other onboard navigation systems. The purpose of the report is to define appropriate levels of accuracy, integrity, availability, reliability, and coverage for DGPS. The starting point is defining a target level of safety (TLS) associated with an acceptable level of risk estimated using the 1991 Port Needs Study (Volpe National Transportation Systems Center, 1991). Note that the Port Needs Study did not include navigation failure and/or error as one of the causes of incidents. In the current analysis, four incident categories (operator errors, errors in judgment, failure to account for currents, and failure to maintain position control) that comprised 30% of the incidents were assumed to represent shortcomings of the navigation function. The study apportions this navigation risk equally among undetected failures, detected failures, and no DGPS failures. The study used failure mode analysis and Markov chain analysis to assess design parameters for the following parameters:

- DGPS Service MTBF
- Design Service MTTR
- Protection limit
- Time to alarm
- Beacon receiver MTBF
- Position plotter MTBF
- GPS receiver MTBF

The study characterized two sets of specifications: one for "typical" procedures, and one for "challenging" procedures. The study recommends developing an implementation plan for the most cost-effective and timely method of implementing the DGPS requirements specified for typical and challenging harbors. A second recommendation involves conducting tests to verify that DGPS service requirements are being met.

Performance tests of DGPS on the newest buoy tenders have demonstrated excellent accuracy (Spalding and Crowell, 1996, 1997). The DGPS test results confirm that the system installed aboard JUNIPER is capable of achieving 2-meter fix accuracy with a 95% probability. The dockside test of the DGPS in Milwaukee, at a wharf including several large cranes, stacks of containers, and other equipment, yielded an accuracy of 3.1 meters over a 15 hour period of continuous (every 15 second) sampling. It is believed that this was due to some blockage of satellite signals and creation of multipath effects. The test also observed several large "spikes" in the data up to 24 meters. This is a similar effect reported by Leica, Inc. (WLB shipboard receiver manufacturer) on the Point Loma, CA broadcast. It was found that these were due to

the DGPS broadcast and corrective action has been taken by the EECEN. The DGPS test results confirm that the system installed aboard IDA LEWIS is capable of achieving 2-meter fix accuracy with a 95% probability. Three of the five tests involved conditions outside of the sponsor's requirements. In two of those tests, IDA LEWIS was unable to achieve 10 meter accuracy. Most of the positioning involved using the DGPS broadcast from Sandy Hook, NJ (nearly 100 miles). Performance was not as good as when the closer Montauk Point radiobeacon was used.

Recently, Ryan, Petovello, and Lachapelle (1998) examined the positioning accuracy improvement that is obtained by augmenting DGPS with single point GLONASS, differential GLONASS, and height constraint. The alternatives were evaluated by running a simulation over a 24 hour period. Field trials were conducted at the University of Calgary under various GPS and GPS-GLONASS masking angles. For both the simulation and the field trials, the availability and reliability performance were analyzed as a function of signal obstruction elevation and the types of augmentation that were implemented. The report examines the reliability of the DGPS installations operated by the Canadian Coast Guard. Although the broadcast DGPS corrections are reliable, a reliable position for the user is not guaranteed because of possible problems such as: user multipath, user receiver blunders, troposphere or ionosphere modeling problems, or masking effects resulting in a weak geometry. Six positioning methods were analyzed:

- DGPS alone
- DGPS and a height constraint
- DGPS and GLONASS
- DGPS, GLONASS and a height constraint
- DGPS and DGLONASS
- DGPS, DGLONASS and a height constraint

The simulation and the field test results showed that augmentation of DGPS with GLONASS and DGLONASS improved both the reliability and the availability of the navigation system. The best conditions were observed with DGPS augmented by DGLONASS and a height constraint.

Mueller, Loomis, and Sheynblat (1995) postulated and evaluated three network architectures that would extend the DGPS service to a proposed wide area DGPS (WADGPS) architecture. They incorporated the idea of a fault tolerant network. An examination of the error mechanisms led to the development of network algorithms for the three WADGPS networks. A new algorithm results in improved performance for two of the three candidate networks.

8.4 Systems and General Advanced Technology Studies

Several studies were waterway evaluation studies that used advanced technology to examine alternative waterway designs. Cook, Marino, and Cooper (1980) used a ship's bridge simulator to examine navigation issues, effect of navigation displays, and the effect of bridge personnel organization during low visibility approaches of a VLCC to a deepwater port complex. Ninety simulated approaches were made with radar, radar with added racons, an automatic radar plotting aid (ARPA), or an ARPA displaying fairway boundary lines. Study recommendations included relocating the mooring master pickup point, providing an anchorage to be used when waiting for a

mooring master, placement and implementation of racons, and the use of special bridge procedures and navigation systems. The study concluded that approaches of VLCCs to deepwater ports are not deceptively difficult or inherently unsafe, but there are some opportunities to mitigate the potential for hazardous navigation and shiphandling problems. O'Hara and Brown (1985) used the CAORF ship's bridge simulator to investigate the relative safety afforded the new Sunshine Skyway Bridge by three alternative navigational system designs that involved specific configuration of channels, aids to navigation, and shipboard navigation aids in the vicinity of the bridge. Nine scenarios were developed to compare bridge safety of four designs during the transit of a 160,000 dwt tanker, generally in adverse conditions consisting of heavy fog or thunderstorms. Numerous other similar studies have been conducted at CAORF and its successor, MSI. Although no published list exists, the Coast Guard R&D Center does maintain a listing of these reports.

Stewart and Alexander (1992) examined the feasibility of using a shore-based experimental automated vessel tracking system to control vessel movements, both for trackkeeping and collision avoidance. The experiment was conducted using vessels from the USMMA. The AVTS was located at USMMA from which helm commands were transmitted to the test vessels. The system was used by an experienced Master and by a USMMA Midshipman Cadet. Although there was some difficulty in the test subjects remembering the most recent helm orders, both the Master Mariner and the Midshipman Cadet were able to effectively maintain the intended trackline. Another experiment involved the same task using radar. The Master's performance was degraded compared to the AVTS. The Cadet declined to participate because of the difficulty encountered by the Master. The Master was also able to effectively control two vessels in a meeting situation using the AVTS, but was unable to do so safely using a shore based radar alone.

Grabowski has researched the effects of using an expert system to assist pilots (see Grabowski and Sanborn, 1992, 1995a, 1995b; and Grabowski and Wallace, 1993). The *Shipboard Piloting Expert System (SPES)* is a real-time knowledge-based system embedded in the EXXBridge Integrated Bridge System. Grabowski examined the SPES's impact on bridge watch team performance and, by extension, on the safety of navigation. An independent variable, voyage stress, was operationalized and measured to account for differing naturally occurring conditions. As expected, the SPES contributed to improved maneuvering and collision avoidance performance as evidenced by multiple measures. When considered in terms of compensating for increased stress levels, the SPES contribution was again found to be better in maneuvering and collision avoidance rather than trackkeeping. The data suggested that the bridge watch team performance is made more uniform with the new technology. Collectively, the results suggested that the SPES technological impact is oriented more towards increasing collective decision quality than minimizing workload.

Grabowski and Georg (1996) provided a state-of-the-art review of the development of integrated bridge systems and intelligent piloting systems. The paper predicted a need for distributed intelligent piloting systems that will make the relevant information available to several ships and shore-based VTS personnel simultaneously using the same display. The paper reviewed human performance using integrated bridge systems focusing on the empirical and operational evaluations of the SPES. The paper concluded that intelligent piloting systems are best considered as value-added enhancement to an integrated bridge or and ECDIS, rather than standalone systems.

Few intelligent piloting systems have been developed which provide expert decision support for *all* types of piloting knowledge. Substantial advances in reasoning, reliability and decision enhancement can be produced by integrating shipboard navigation systems (including piloting expert systems) with vessel traffic services and real time port environmental data.

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9.0 SUMMARY OF STUDIES FOCUSING ON COST ISSUES

9.1 Coast Guard Costing Overview

Cost development/allocation in the US Coast Guard is usually based on direct costs incurred by an operational unit, personnel costs attributable to that unit, and the cost of services provided to the unit by other operational and operational support units. These costs are often a combination of actual costs incurred and average costs associated with assignment of personnel or the operation of boats, ships and aircraft. In some cases, administrative costs are allocated to the unit.

Actual operating costs for travel and per diem, supplies, equipment, maintenance, fuel, and other purchases are available directly from the Allotment Fund Code (AFC) in the accounting system. To supplement those areas where incurred costs are not available, "Standard Rates" have been established to be used in computing reimbursable charges. The standard rates "reflect all readily identifiable cost elements." The standard rates apply to cutters, aircraft, small boats, personnel, pollution clean-up equipment, vehicles, outpatient visits and inpatient days, and aids to navigation.

The standard rates for personnel apply when the personnel used are not involved in another unit for which other standard rates apply (e.g., cutter, aircraft, boat) and not for extended periods of time. The standard rates include costs for pay, allowances, government contribution to employee benefits, training, and permanent change of station costs.

In addition to the standard rates for reimbursable activities, tables of detailed standard personnel costs have been developed for use in costing proposals. Separate tables are available for personnel costs, PCS costs, Operating and Maintenance (O&M) costs, training costs, and medical costs.

In many ways, the intent of the Coast Guard costing system is activity-based. The direct cost of operating multi-mission units is obtained from the existing accounting system and unit operating costs are typically allocated to the operating programs based on reported program utilization (e.g., aircraft hours, cutter days) or some other allocation mechanism. One question has always been the allocation mechanism for "overhead" costs. Some overhead elements have a causal relationship to particular operations while others are very generic and only support the overall existence of the Coast Guard. Generally, overhead is computed as a fixed percentage (currently 30%) of operational costs rather than examine any functional relationships to define transaction-related cost drivers. In addition, there is no identification/classification of costs as fixed or variable, controllable or noncontrollable, avoidable or nonavoidable, linear or nonlinear, and/or sunk. These categorizations have significant implications when evaluating programs and estimating actual cost savings or increases associated with program decisions. (Armacost, 1995)

9.2 Aids to Navigation Costing Approaches

In general, aids to navigation program costs have been developed for two purposes: to describe the costs of current activities, and to evaluate the expected cost of future activities, particularly in terms of alternative actions. Most of the operating units

involved in aids to navigation are single mission units. For example, ANTs, Depots, and all coastal and smaller buoy tenders are generally 100% ATON. For those units, operating costs and fuel costs can be accumulated, as can personnel costs. In some instances, the personnel costs are estimated using standard personnel costs (that include salary plus other recurring and nonrecurring support costs) applied to either the actual personnel assigned or to the authorized personnel allowance. Some costs are centralized at the District and are not easily identified with individual units. Boat maintenance costs vary, and typically, a unit is allocated a cost equal to the amount that was provided to the District to support the particular boats operated by a given unit (e.g., ANB, BUSL, TANB). How much a District actually spends on maintaining individual boats is not captured in any of the cost analyses. The amount spent on aids to navigation hardware is controlled by Headquarters and is generally not allocated to individual units.

For WLBs, the ATON costs are usually determined by allocating the total costs based on the proportion of operating hours spent in aids to navigation operations. It is not clear whether this is a proportion of total program operating hour, or total operating hours (including training, etc.). Larger shore units that have other missions (e.g., Bases) have typically been allocated 100% to ATON. Generally, direct administrative costs (District and Headquarters staff) are not allocated. Rather, those costs are reflected in the standard rates assigned to personnel. Some algorithms allocate operational unit administrative costs (e.g., Group office ATON) based on estimated percentages of activity in the program.

Based on these methods of compiling or estimating costs, it is difficult to obtain a refined cost picture associated with aids to navigation activity in a particular area or for a particular unit. In many of the cost analyses involving alternative servicing units, aids to navigation hardware costs and administrative costs are not included because it is assumed that they are the same under all alternatives. However, when different equipment is involved (e.g., replacing a buoy with a light), equipment costs do matter.

Finally, most of the aids to navigation studies involving costs have considered life cycle costs. They have typically used discount rates and planning horizons dictated by official guidance in place at the time. Most of the studies did not include a sensitivity analysis with respect to any of the cost parameters.

9.3 Aids to Navigation Studies Involving Costing Approaches

Several studies had cost as a primary focus of the work. Thacker (1989) and Tung, Skaliotis, Goeddel, Flahive, and Cook (1990) conducted cost and performance evaluation of a three year trial program of commercial on-site servicing of aids to navigation. Although the two studies produced different results with respect to performance, they both concluded that contracting the servicing of aids to navigation was more expensive than conducting the program internally with Coast Guard personnel and equipment. Fremont-Smith (1994) examined the buoy body shortage and evaluated the costs of recapitalizing the buoy inventory, then valued at $74 million. Annual expenditures of $4 million for buoy replacement were recommended. The Service Life Extension Project study was an explicit cost analysis of the WLB renovation program.

A number of other studies included cost as a primary criterion in evaluating the primary purpose of the study. Daidola, Basar, Reyling, and Walker (1991) evaluated the

results of the buoy technology survey to rank order areas for the various technologies based on economic savings over the 30 year planning horizon. The highest priority item is the use of FRP and GRP materials with estimated savings in excess of $63 million followed by Systems Approach to Design with estimated savings of $54 million. The study cautions that the results are dependent on the assumptions about particular levels of savings. Associated with the buoy technology survey, Rosenblatt (1990) developed a buoy technology information system that included replacement cost, preparation cost, and monthly servicing cost (1989 dollars).

The buoy maintenance study (Murphy, 1995) used a detailed cost analysis to evaluate several alternatives for consolidating and improving buoy maintenance operations in Atlantic Area. All of the service force mix studies used cost as a primary criterion for evaluating the different alternatives. The Booz-Allen study was the first major study to include life-cycle costs for evaluating alternatives (Booz-Allen 1970a, 1970b, 1970c). Although the reports included the costs in various tables and the analysis, the derivation of the costs is not included in the reports. The next major service force mix study, the 1983 SRA study (US Coast Guard, 1983), included a detailed development of the costs used to evaluate the alternatives. The study noted that the costs allocated through the Coast Guard cost centers did not include all aspects of the operations, and therefore, only used constructed (derived) costs in the analysis to compare buoy tender options. The several studies comprising the SFM 2000 study (Brown, et al., 1992; Brown, 1993; and Brown, Bucciarelli, and Leo, 1994) used life cycle costs to evaluate alternatives (including contracting construction work). The SFM 2000 studies also evaluated the outcomes using a sensitivity approach. However, the sources for the cost elements are not included in SFM 2000. Finally, SRAMA (US Coast Guard, 1994) used life-cycle costs primarily for evaluating buoy boat alternatives. This analysis represented a systems view of costs.

9.4 Cost Issues References

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10.0 METHODS AND MODELS USEFUL FOR FUTURE ANALYSES

Of the 137 studies reviewed in the Annotated Bibliography (Volume II), 34 studies had a secondary classification of "Modeling and Analysis" and 43 studies had a secondary classification of "Human Factors." The modeling and analysis studies were largely associated with approaches to evaluating the service force mix, while others were associated with positioning, characteristics of DGPS, and analytical models of navigation. A few models address overall performance effectiveness measures for waterways and risk issues. Most of the human factors type studies involved simulator or at-sea experimentation to evaluate the performance of aid systems, both visual and electronic.

10.1 Service Force Mix Methods and Models

The most recent model to address the service force mix is the SFM DSS used in the SFM 2000 study and follow on analyses of WLIC and BUSL requirements. The general nature of the DSS is described in Section 7.4.1. More complete descriptions are included in Brown, et al. (1992) and in Bucciarelli and Brown (1995). The DSS is a reasonable model to evaluate the adequacy of an assigned set of servicing forces. It uses composite time estimates when creating the various tours that select the aids to be serviced on a particular trip. The sensitivity results from the model are very useful for evaluating the effects of service time changes, such as improvements in the time to position an aid using the new DPS. The model is robust in its ability to be applied to all classes of buoy tenders and buoy boats.

The SFM DSS operates in conjunction with a GIS to construct the servicing tours. The model logic could be used with another method of determining the servicing tours and remain effective, depending on whether the model was a deliverable to the Coast Guard. As alternative aid arrangements are developed, possibly with the incorporation of ECDIS, the SFM DSS could be rerun to evaluate the effect of reduced numbers of visual aids. The same analysis could be undertaken to evaluate the effect of the changed servicing intervals as recommended by Fremont-Smith (1994). Given the results of SFM 2000, these changes would primarily affect the WLMs only. Note the Bucciarelli and Brown (1995) indicated that the WLBR/WLMR mix of 12/19 (31 total) or 13/17 through 19/11 (30 total) would all accomplish the mission. The current level of 16 WLBRs is dictated by the multimission requirements. The existing results can be used to estimate the effects of servicing or aid assignment changes without rerunning the model. Such a parametric study would be useful.

The other model that was developed and tested, but never applied to determine the service force mix, is ANGEL, a discrete event simulation that replicates a buoy tender's activities in a servicing tour (Kingsley, Klesczewski, and Smith, 1990). A robust algorithm was developed as part of this research to determine the servicing tour. As with the SFM DSS, the complete model operated over a year period. The model approach appears sound and conceptually is similar to the SFM DSS. It appears that ANGEL attempts to more accurately represent the buoy tender actions. It handles discrepancy response in the model, whereas the SFM DSS computes additional resource time associated with expected discrepancy response. The ANGEL model and associated route planning model could be applicable in the future, but additional

programming and development would be required. The GIS approach used by the SFM DSS appears to be a very efficient way of handling the large data entry workload.

10.2 Aid/Waterway Performance and Risk Methods and Models

Greenberg et al. (1986) developed a Resource Management Tool that incorporated a benefits hierarchy and a cost hierarchy both of which contained several levels of attributes. The benefits hierarchy included safety (avoidance of accidents), timeliness (avoidance of delays) and other benefits (e.g., mariner interests, CG interest, other government interests, and public interests). The cost hierarchy considered both CG costs and other federal government costs. A value tree approach was then used to develop weights for the lowest level attributes and various resource allocation alternatives could then be compared on the several attributes and a resulting weight or value computed for each alternative that indicates the ranking of the alternatives. While this approach is valuable as a first approximation, the structure of the tree (where particular attributes such as SRA and RA are located) can bias evaluations. Greenberg et al. included a good discussion of Multiattribute Utility Theory, but the resulting application should be reexamined carefully before the approach is used again.

As indicated in Section 5.4.4, following submission of this report, the project was discontinued (US Coast Guard, 1994b). The SRAMA study noted that the lesson learned from this project was that quantitative measures are difficult to develop. In particular, this approach emphasized the use of expected benefits and costs. Events such as groundings are rare, and even if the probabilities could be estimated accurately, slight improvements would not result in significant expected benefits. Because of the difficulty in estimating the probabilities of these "rare" events, pursuing this approach was not supported. SRAMA noted that factors such as human safety, enhanced timeliness (e.g., enabling night navigation) or other benefits might tip the scale in a full analysis of a real problem. The need for further analysis in this area was indicated by Casey, Watros, and Hall (1995) as described previously. Risk analysis is able to address rare events in a number of ways. One approach is the use of distributions of extremes, an approach that has not yet been used in Coast Guard waterway analysis.

The results of a number of years of man-in-the loop simulation studies has facilitated the development of the *Waterways Design Manual* (Smith, 1992) that provides supplementary guidance for aid selection and arrangements for marking waterways. The manual includes a model for estimating the Relative Risk Factor (RRF) that can be used to compare alternative waterway and aid designs for a specified design vessel. The RRF is a measure of the chance of the vessel grounding during a passage through the waterway. SRAMA noted that the RRF is not the "probability of grounding" and is not an absolute measure. Therefore, it is not useful for estimating the expected consequences associated with some number of transits of the waterway. Nor is it useful for comparing one waterway to another. These limitations are clearly indicated within the manual itself. Nonetheless, the RRF remains a viable tool for its intended purpose. The future use of RRF is unknown because the implementing computer program (ARRF) was not included for migration to Standard Workstation III.

The Coast Guard is presently developing a Waterways Evaluation Tool (WET) that is intended to be able to permit interwaterway comparisons (Volpe National Transportation Systems Center, 1996a). This approach, like the Greenberg et al. (1986) approach, primarily involves the use of value trees. Where Greenberg et al.

evaluated benefits and costs, WET uses the value trees to evaluate both the performance and importance of waterways. Using these two measures, a Significant Performance Index is computed that provides a baseline measure of performance with respect to the most important function(s) of the waterway. Separate value trees will be developed for each of five Coast Guard strategic goals. The value trees use both objective and subjective scoring procedures. The subjective scoring typically involves a 1 - 5 scale. Weights for the various elements are provided for general waterways, but certain users may specify particular weights for given waterways. For most performance elements, an additive approach is used to aggregate the scores. The functional requirements report only contains partial information on the various value trees.

As discussed in Section 5.4.5, the proposed WET methodology using value trees makes some unstated assumptions about the value functions (e.g., risk status, mutual preferential independence). In addition, the method by which the weights for the various elements and sub-elements are obtained for an individual waterway is not described in the functional requirement. The general waterway weights were developed by the Technical Advisory Team using Groupware. The issue of interpersonal value/utility comparisons has not been addressed. The report would lead one to believe that evaluations of different waterways by different users can lead to meaningful comparative results. This is one of the remaining unresolved issues in decision theory and stands as a roadblock in the meaningful application of WET. With respect to SRA and RA, their location in the mobility value tree seems to indicate a diluted importance (simply from the structure of the tree) for those elements. While WAMS may not be giving a good systems analysis of the waterway, it is not clear that WET as proposed in this report will either.

10.3 Simulation Methods and Models

The simulation methods in Section 10.1 were used to evaluate various servicing alternatives. The simulation methods of interest here are those used to represent or evaluate the performance of aid systems and navigation aids. Several fast time simulations have been developed for waterway evaluation. Hwang (1986) developed the navigator model that was used in Kaufman's (1985) compressed time simulation. It is not clear whether the navigator model was a control model or if it included a mechanism for obtaining position information from aids to navigation that marked the waterway. The preliminary simulation model developed by Clark et al. (1978) did include an analytic model for estimating position information from visual aids. The full model was never developed. No operating fast time simulation model that obtains position information from visual aids has been identified.

The dominant use of simulation has been the use of man-in-the-loop simulators, principally at MSI/CAORF and at the USCG Academy (SCANTS), to evaluate the system performance in the presence of various visual and radionavigation aids. This simulation method has proven very effective in evaluating aid arrangements and the use of various electronic displays. It remains a viable tool for future evaluation.

10.4 Cost Methods and Models

The costing methods described in Section 9.0 are generally consistent with the methods that are in use throughout the Coast Guard, but lack consistency among

applications. The R&D Center is developing a life cycle cost model identified as *Project Analysis & Cost Estimation (PACE)*. The PACE model will be available on Coast Guard computers. Use of the PACE model will provide consistency and accuracy in computing costs of alternatives. PACE will become the standard system to be used in the Coast Guard for life cycle cost analyses. It will use approved rates for personnel and units as well as approved discount factors. It is expected to be implemented in FY 1999.

11.0 UNRESOLVED ISSUES

The review of the many studies that have addressed various facets of aids to navigation yields several issues that remain unresolved. Several of these will likely require resolution in the near future as pressures for increased levels of service while reducing costs continue to mount. The following list is an initial identification of the issues. The studies referenced in this report provide a background for developing them further. The various issues have been grouped by functional or managerial area.

Aid Development Issues

- Articulated beacons--Are they feasible? What are the costs? What are the effects on servicing requirements? Placement? Maintenance? Replacement?
- Progress in plastics--What are the potential savings? What are the opportunities for using plastic buoys as steel buoys deteriorate? Annual buoy cost is $4 million--what servicing savings will accrue?
- Lighting systems--How can the recharge cycle be extended? Lamps or batteries? Better lights to increase nominal range and decrease numbers of aids?
- Guano--How to minimize need for frequent cleaning visits for solar panels? Guano shedding coatings?

Service Force Mix Issues

- SRAMA Validation--SRAMA (1994) mix supposed to be validated in five years
- Surge capacity--How to define and account for it explicitly?
- Servicing policy change--What is the effect of the servicing policy change?
- Aid reductions--What are the possible savings for various levels of aid reductions? Does the number of aids drive the service forces, or is it their location?

Aid Mix

- Visual/DGPS--ECDIS--The trade-off between visual aids and ECDIS is unknown--how is information obtained from each and how is it integrated when both are present at various levels?
- Cognitive analysis--How does the mariner obtain meaningful position information from visual aids or from electronic displays?
- User difference--How sensitive are different user groups to changes in the aid mix? How does it affect their ability to navigate safely?

Cost

- Accurate costing--How can the controllable costs be identified that would be affected by program change decisions? How can the real savings be identified?

Analysis

- Capability--How can the Program Manager maintain an analysis capability to permit ongoing program evaluation? Is there a need for a broader focus analysis support group?

- Models--Without an analysis capability, no analytical models are maintained. What analytical models are needed/useful for management? SFM DSS? RMT?
- Automated Relative Risk Factor (ARRF) computer program--May loose the capability to evaluate waterway risk if ARRF is not resurrected.
- Buoy Technology Information System (BTIS)--The system has been dormant and not maintained.

Advanced Technology

- Small users--How do small users benefit from technology advances (e.g., DGPS) if they do not have ECDIS or ECS capability? Are there chart independent technologies for assisting the small user?
- Applicability--What is the scope of applicable areas for advanced technologies? Are they useful in the ICW? Can they replace daybeacons and lights?
- CW interference DGPS--Is CW interference with DGPS signals a problem? What backup systems may be needed if CW interference occurs?

The above listing raises a number of questions that suggest further work. The Aids to Navigation Program Manager should formally frame these issues and identify particular ones that should be addressed by the Coast Guard. Other issues may be addressed by industry, other government agencies, or be overtaken by events.

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